

PERFORMANCE CHARACTERISTICS OF THE DEEP SPACE 1 FLIGHT SPARE ION THRUSTER LONG DURATION TEST AFTER 21,300 HOURS OF OPERATION

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ABSTRACT

A long duration test of the DS1 flight spare ion thruster (FT2) is presently being conducted at the Jet Propulsion Laboratory. To date the thruster has accumulated over 23,500 hours of operation, and 190 kg of Xenon propellant, over 230% of the initial design life. The primary objectives of the test include the processing of 200 kg of Xenon propellant, the identification of unknown failure modes, the characterization and drivers of these failure modes, and to measure performance degradation as the thruster wears. The test is fitted with an extensive array of diagnostics to measure engine wear and performance degradation. To date the most notable erosion processes include severe discharge cathode keeper erosion, accelerator grid erosion, reduction in electrical isolation of the neutralizer assembly, and deposit formation within the neutralizer orifice, reducing margin from plume mode. Over the past 23,500 hours of operation, performance degradation has been minimal, and it is anticipated that the above erosion processes will not preclude the thruster from processing over 200 kg of Xenon.

INTRODUCTION

NASA's 30 cm diameter xenon ion thruster technology is being validated for use in planetary missions by the Advanced Ion Propulsion System (AIPS) program and previously by the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) program. The key objective of these programs is to verify and flight qualify ion thruster technology by providing spacecraft managers with sufficient information on ion thruster performance, reliability and spacecraft interactions. The NSTAR technology validation program included extensive ground testing and on orbit verification of xenon ion thruster technology with the

Deep Space One spacecraft (DS1). As part of the NSTAR ground test program, an engineering model thruster, designated EMT2, was operated for 8200 hours in a long duration test at the NSTAR full power point. Two flight unit thrusters were fabricated, FT1 and FT2, with minor modifications to EMT2's design due to thermal and structural considerations⁵. FT2 was designated the ground test thruster to conduct the long duration life test and additional thruster tests before the launch of DS1. Although the design modifications to FT2, were not expected to cause significant change in thruster performance, ground testing of the spare flight thruster, was initiated before the launch of DS1. Ground testing of FT2 began on October 5, 1998 and 412 problem free hours of operation were accumulated before the DS1 launch.

FT1 was designated the DS1 flight thruster. After qualification testing, FT1 was integrated onto the DS1 spacecraft, which launched on October 24 1998. Operation of FT1 in space began in November 1998. After thrusting for over 1800 hours and processing 12 kg of xenon, the DS1 spacecraft performed a flyby of asteroid 9969 Braille on July 28, 1999. An additional 52 kg of xenon was processed by FT1 to accomplish the DS1 flyby of comet Borrelly in September 2001. A detailed discussion of the operation and performance of FT1 on the DS1 spacecraft are given in references. [3-5].

A long duration test of the DS1 spare flight thruster (FT2) is being conducted at the Jet Propulsion Laboratory. The thruster has operated continuously, since the DS1 launch, accumulating over 23,500 hours, and processing over 190 kg of xenon propellant, to date. Thruster performance data and operational characteristics, over the full DS1 throttle range, have been collected and analyzed during the course of the on

going test, to aid in the diagnoses and understanding of the processes of failure and performance degradation.

This paper will present the performance variations and degradation processes experienced by FT2 over the first 21,306 hours of operation. Although FT2 has operated for over 23,500 hours to date, detailed data analysis has only been performed on the first 21,306 hours of operation. The thruster continues to perform nominally and at present no problems have been identified that would prohibit the processing of 200 kg of xenon as the test progresses.

TEST PLAN

The initial objectives of the long duration test of FT2 were to demonstrate 150% (125 kg) of the DS1 mission through put capability, identify any unknown failure modes, characterize known failure modes, and determine how engine performance changes with operating time. Although the processing of 125kg of propellant was accomplished in December of 2000, it was decided to continue the test to demonstrate even higher throughput capability, to meet the needs of future more ambitious deep space missions. Future missions such as Dawn require 130 kg per ion thruster, and missions such as Neptune Orbiter, Venus Sample Return, and Europa Lander would require over 200 kg of propellant throughput. It was therefore decided to continue the test to demonstrate 200 kg throughput capability, and to test the thruster to failure.

The DS1 mission and solar electric propulsion missions in general, require thrusters to be throttle-able, to maximize use of available solar array power, as a function of mission trajectory (distance from the sun). The DS1 30 cm ion thruster is throttle-able over a range of 0.5 to 2.3 kW. It was decided to incorporate this throttle-able characteristic of the engine into the test plan of FT2, to study thruster wear characteristics, operational difficulties, and potential failure modes as a function of throttle level. However, to obtain useful data on wear characteristics associated with a particular operating point, the thruster needs to be operated for several thousand hours at a specific set of operating parameters. The test plan has therefore been to operate for approximately 5000-hour intervals at a specific power point, with the major emphasis on the full power point to maximize xenon propellant throughput.

During normal operation, performance measurements are taken every 100 to 200 hours, including measurements of electron backstreaming limit, permeance, screen grid transparency to ions, doubly ionized beam content, and thrust. General electric parameters are recorded every 5 seconds, and location of the thrust vector every 300 seconds. In addition to

normal operation, short duration throttling tests and sensitivity tests are conducted every 2000 to 3000 hours. During the throttling tests, six power points are investigated to measure the performance characteristics over the 0.5 to 2.3 kW throttling range as the thruster wears. In addition to the general performance measurements, at each throttle point, the beam current density profile is recorded, and a neutralizer characterization is performed, to determine flow rate margin from plume mode. Every 1000 to 2000 hours, video data is recorded, using a three-axis stage video camera system, inside the vacuum chamber. Video of the discharge cathode, downstream face of the accelerator grid, and neutralizer cathode is recorded, in addition to general inspection of the thruster exterior.

Prior to the DS1 launch, FT2 was initially operated at 1.96 kW (TH12) for approximately 500 hours. Since then the thruster has been operated in 5000-hour test segments first at full power (TH15), then half power (TH8), back to full power, and then minimum power (TH0). From 21300 hours to the present day, thruster operation has resumed at the full power point, in part to facilitate the processing of 200 kg of xenon propellant. The 200 kg throughput milestone is expected to be reached by August 2002. Details of each power level can be found in Table 1.

THRUSTER DESIGN AND OPERATION

A schematic diagram of the 30-cm-diameter NSTAR flight thruster is shown in Fig. 1. The thruster is comprised of four major functional components, the discharge cathode, discharge chamber, ion optics (accelerator) assembly, and the neutralizer assembly. An ion thruster operates by ionizing neutral xenon gas in the discharge chamber by electron collision with neutrals. The positively ionized xenon propellant is then focused and electro-statically accelerated through a two-grid electrode system, the ion optics. The neutralizer cathode acts as a plasma bridge between the neutralizer and beam; supplying electrons to charge neutralize the ion beam.¹

The FT2 thruster employs a spun titanium discharge chamber, with a three-ring cusp magnetic field design. The discharge cathode, located at the rear of the chamber, is the source of electrons to the discharge chamber. The magnetic field is used to improve ionization (propellant utilization) efficiency by increasing the residence time of electrons in the discharge chamber. By forcing electrons to gyrate around the magnetic field lines, before they are collected by the anode, the number of ionizations is greatly increased. The discharge chamber is enclosed in a perforated plasma screen to prevent beam neutralizing

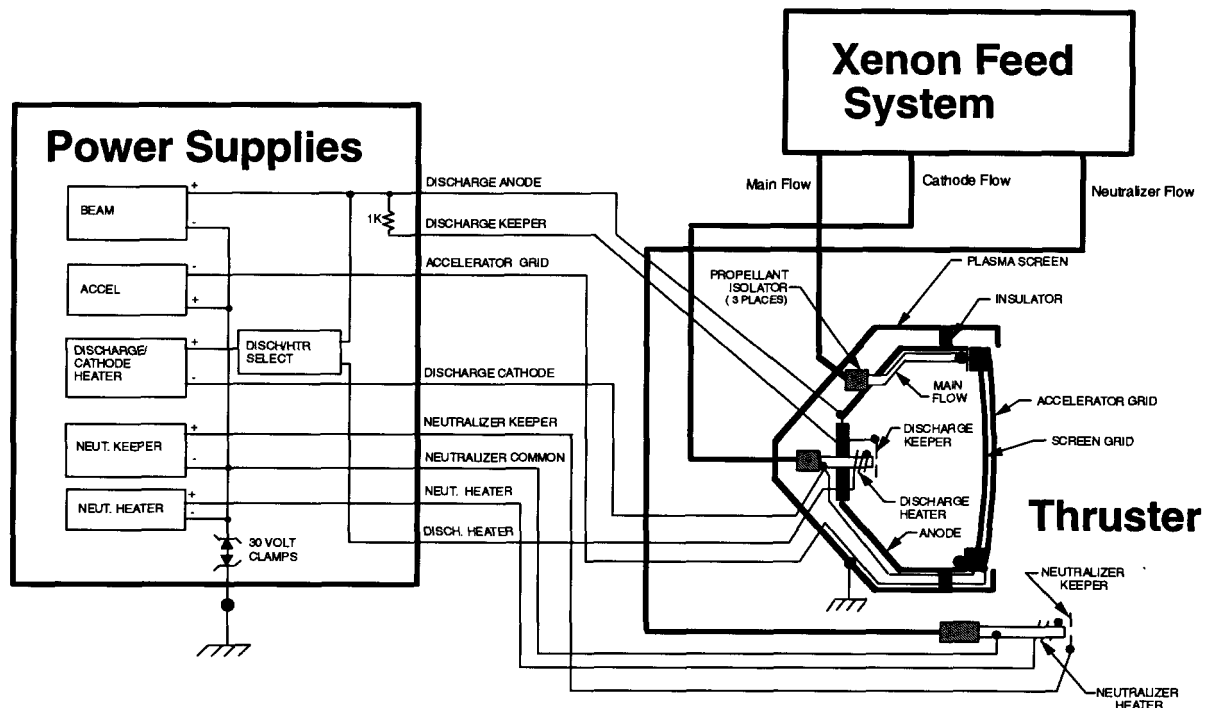


Fig. 1 Schematic of FT2

electrons from reach high-voltage surfaces. The two-grid molybdenum optics assembly is located downstream of the discharge chamber. Details on the thruster design can be found in reference [1].

The flight thrusters, both FT2 and the DS1 thruster (FT1), incorporate several minor design changes not in the EMT2 design. The design modifications improved the efficiency, sputter containment, and radiative properties of the discharge chamber. These design changes were validated by analysis or short duration tests and were not expected to have a negative impact on engine performance or wear characteristics. Details on these design changes can be found in reference [2].

THROTTLE TABLE

The DS1 ion thruster was designed to be throttle-able to take advantage of the differing amount of available solar array power, as a function of mission trajectory. The spacecraft thruster has a total of 50 power (throttle) points. For the long duration test, a total of 15 power points have been designated. Table 1 shows the accompanying operating parameters for each throttle point. The designation TH is given for each ground test power level, with a minimum power of 0.5 kW at TH0, up to full power, 2.3 kW at TH15. The throttling tests mentioned earlier are performed at TH0, 3, 6, 9, 12, and 15. For each throttle point the beam current and voltage are controlled. As a result the exhaust velocity, and therefore I_{sp} are held constant. Additionally, as the

beam current set point is close loop controlled by the discharge power supply, the thrust is also constant (to lowest order), assuming the accelerator grid voltage is sufficiently negative to prevent electron backstreaming. For each throttle point the flow rates are set to maximize propellant utilization efficiency, while limiting the production of doubly charged Xenon ions. The neutralizer flow rate is set to minimize propellant loss, as xenon flowing through the neutralizer is un-accelerated. Neutralizer flow rate is maintained with sufficient margin to prevent plume operation; a mode that leads to increased neutralizer surface erosion.²

VACUUM FACILITY

The long-duration test of FT2 is being conducted in a 3-m-diameter by 10-m-long vacuum chamber pumped by three CVI cryopumps and three xenon cryopumps, for a total xenon system pumping speed of 100 kL/s [12]. This pumping system provides a base pressure of less than 4×10^{-6} Torr at the full power flow rates. The pumping surfaces are regenerated after accumulation of 10 kg Xenon. Cryopump regeneration exposes the engine to a primarily Xenon atmosphere at a pressure of about 1 Torr. The cathodes are purged with xenon during these exposures and are conditioned after the subsequent pump down to high vacuum. After the pump regeneration, there is usually a temporary increase in neutralizer keeper voltage and in the magnitude of neutralizer common voltage with respect to facility ground.

Table 1. NSTAR Thruster Throttle Table

NSTAR Throttle Level	Nominal Thruster Power	Beam Supply Voltage	Beam Current	Accelerator Grid Voltage	Neutralizer Keeper Current	Main Flow	Discharge Cathode Flow	Neutralizer Cathode Flow
	kW	V	A	V	A	sccm	sccm	sccm
TH 0	0.52	650	0.51	-150	2.0	5.98	2.47	2.40
TH 1	0.66	850	0.53	-150	2.0	5.82	2.47	2.40
TH 2	0.75	1100	0.52	-150	2.0	5.77	2.47	2.40
TH 3	0.91	1100	0.61	-150	2.0	6.85	2.47	2.40
TH 4	1.02	1100	0.71	-150	2.0	8.30	2.47	2.40
TH 5	1.12	1100	0.81	-150	2.0	9.82	2.47	2.40
TH 6	1.24	1100	0.91	-150	2.0	11.33	2.47	2.40
TH 7	1.34	1100	1.00	-150	2.0	12.90	2.47	2.40
TH 8	1.46	1100	1.10	-180	1.5	14.41	2.47	2.40
TH 9	1.58	1100	1.20	-180	1.5	15.98	2.47	2.40
TH10	1.72	1100	1.30	-180	1.5	17.22	2.56	2.49
TH11	1.85	1100	1.40	-180	1.5	18.51	2.72	2.65
TH12	1.96	1100	1.49	-180	1.5	19.86	2.89	2.81
TH13	2.08	1100	1.58	-180	1.5	20.95	3.06	2.98
TH14	2.20	1100	1.67	-180	1.5	22.19	3.35	3.26
TH15	2.33	1100	1.76	-180	1.5	23.43	3.70	3.60

The walls of the vacuum chamber are lined with graphite panels to reduce the amount of facility surface material that is back sputtered onto the engine surfaces and diagnostics. Graphite is used as carbon has a high surface binding energy, making it more resistant to sputter erosion. A quartz crystal microbalance (QCM) is used to measure the amount of back sputtered material onto the engine. The QCM is located next to the engine, in the same plane as the grids. The QCM provides real time measurements of deposition rate, allowing the test operators to determine if a facility related issue is causing an increase in the amount of back sputtered material. Details of the QCM back sputter rates can be found in reference [2].

The propellant feed system has two mass flow meters in each of the main, cathode and neutralizer flow lines. The downstream flow meter in each line is used to measure the flow rate to an accuracy of ± 1 percent. The upstream flow meters are used as flow controllers. The output signal from each controller is used to actuate a solenoid valve that maintains the flow rate at the set point in each line. Details of the flow system can be found in reference [2].

The laboratory power supplies used to run FT2 are the same as those used for the 1,000 hour test and for the last 5,200 hours of the 8,200 hour test of EMT2.^{6,8} They have similar capabilities to the flight PPU with some difference in the cathode start circuits. The primary difference in the electrical design of FT2 to DS1 is the reference to facility ground, as opposed to spacecraft

ground. However, the reference potential for both FT2 and the DS1 thruster is neutralizer common.

A computer data acquisition and control system is used to monitor facility and engine conditions as well as control the power supplies. Engine electrical parameters are measured to within ± 0.5 percent, and the system samples and stores data at ~ 5 second intervals. It is programmed to shut down the thruster in the event of a facility problem or out-of-tolerance condition on certain engine parameters. This allows the system to run autonomously.²

TEST DIAGNOSTICS

An extensive diagnostics package is used to characterize the performance of FT2 over time. A thruster vector probe mounted downstream of the thruster, at the end of the tank, is used to measure the location of the thrust vector, a key parameter for spacecraft operators. The probe design and operation is described in greater detail in reference [2]. The ion beam characteristics are measured using an ExB probe and a faraday probe. The ExB probe is located downstream of the thruster, and is used to measure the ratio of doubly to singly charged ions in the beam. The faraday probe, is used to measure the radial beam current density profile, and is biased negative of facility ground, to repel electrons. Thrust measurements are made directly with a modified version of the GRC inverted pendulum thrust stand. Specific details on the operation and design of the ExB probe, thrust vector probe, and thrust stand can be found in reference [6].

A three-axis positioning stage inside of the vacuum chamber is used to move two video cameras and light fixtures to allow photography and video recording of the accelerator grid, neutralizer cathode, and discharge cathode surfaces. The main camera provides sufficient resolution to measure erosion patterns on the upstream surface of the accelerator grid and of the neutralizer orifice, keeper and casing. One of the cameras is also capable of focusing through the grids to allow imaging of the discharge cathode keeper and orifice. A laser profilometer is also fixed to the stage, for detailed measurements of the accelerator grid erosion pattern.

LONG DURATION TEST RESULTS

Throttling Test Results

Results of throttling tests over the full power range (see table 1) are shown in Figs. 2, 3 and 4. Fig. 2 is a plot of the measured thrust as a function of thruster power, at several times over the course of the test. Fig. 3 is a plot of specific impulse versus thruster power. The thrust and specific impulse at each throttle point have remained relatively constant over the past 21,000+ hours of operation, with minimal (~ 4%) reduction at the higher power levels, observed from 16,000 to 22,000 hours. The substantially lower specific impulse at the 0.5 kW operating point is primarily due to the lower beam voltage at TH0. The general trend to increasing specific impulse with power is primarily the

result of reduced cold flow losses through the neutralizer, as power level is increased. At the lower power levels, the un-accelerated neutralizer flow is a higher percentage of the total flow, resulting in lower propellant utilization efficiency. The thrust of an ion thruster is proportional to the product of the beam current and square root of the beam voltage. Similarly, the specific impulse is proportional to the beam voltage. As both beam current and beam voltage are held constant, the thrust level and specific impulse—to lowest order—are also fixed. The minor variation in thrust and Isp, as the thruster wears, is most likely attributed to a slightly higher double ion current in the beam.

Thruster efficiency is plotted as a function of thruster power in Fig. 4. Thruster efficiency is the ratio of power converted into directed kinetic energy (thrust) to the total power consumed by the thruster. Thruster power is proportional mass flow rate and the square of the specific impulse. The reduced total efficiency at the lower power levels is also a result of more substantial cold flow losses through the neutralizer, in addition to the lower beam voltage at TH0. Variations in thruster power required to produce a given thrust are due primarily to changes in the discharge power as the thruster wears. The total efficiency has also remained relatively constant for each throttle point over the past 22,000 hours. However, an approximate 3% reduction

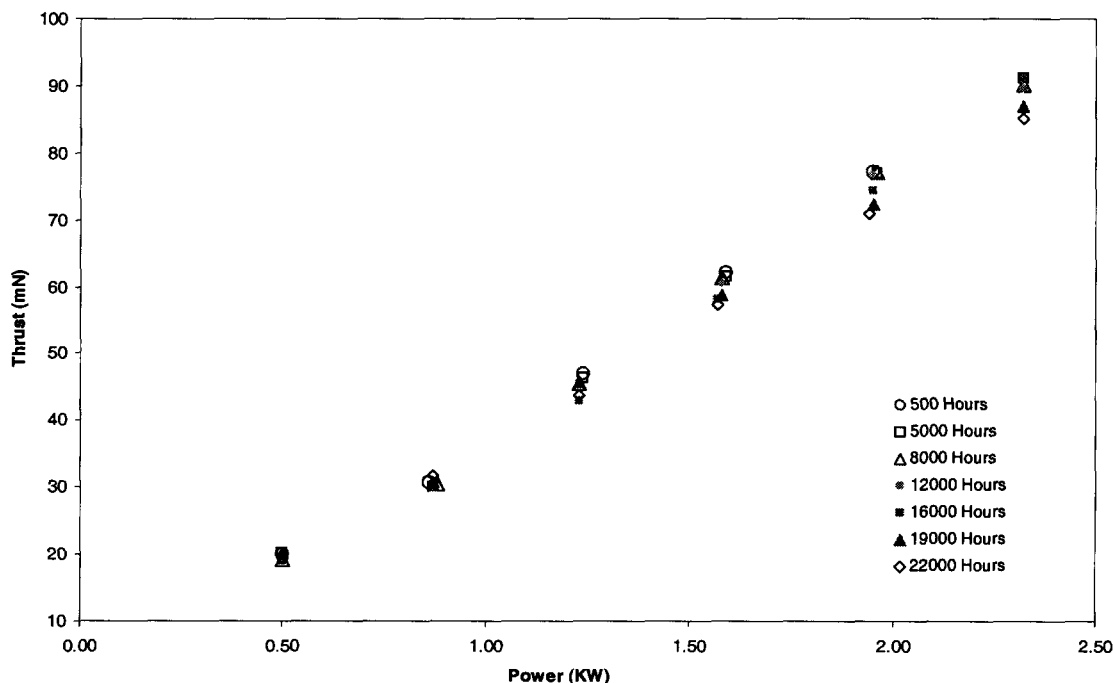


Fig. 2 FT2 Thrust Versus Power

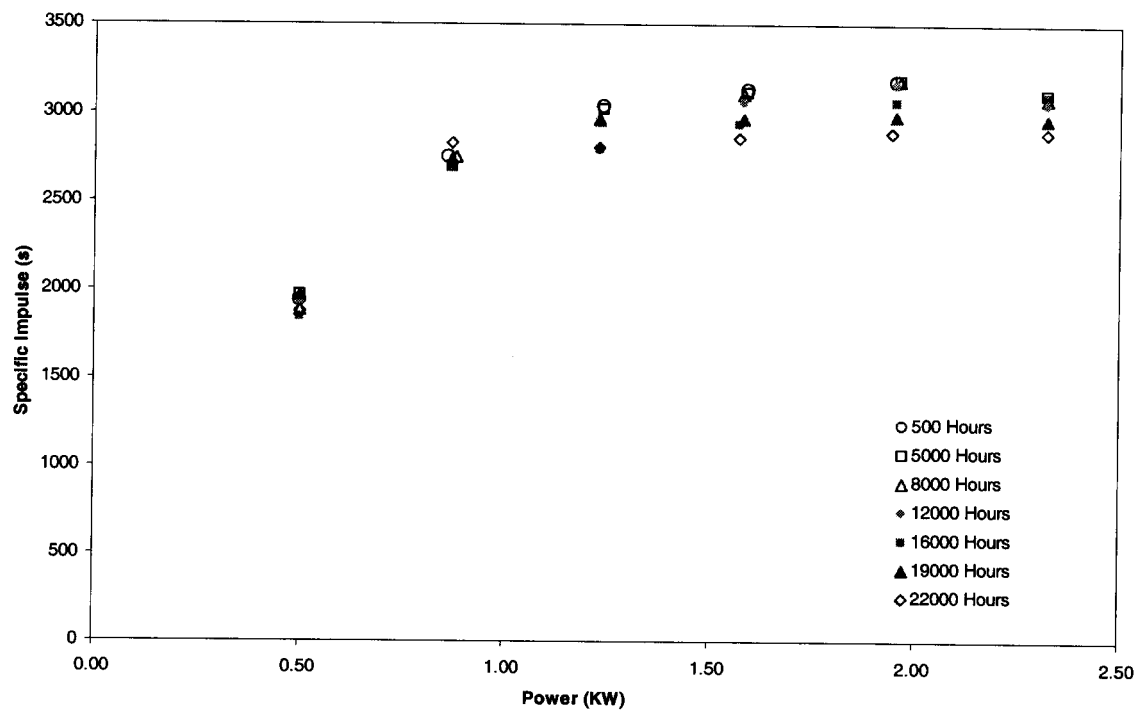


Fig. 3 FT2 Specific Impulse Versus Power

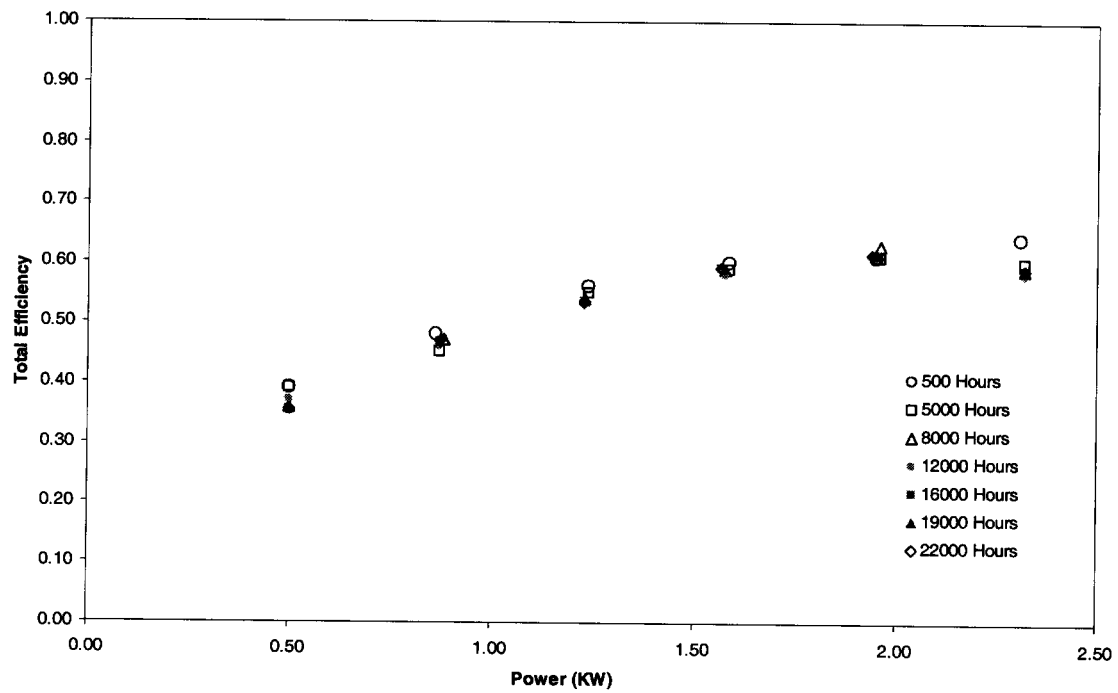


Fig. 4 FT2 Thruster Efficiency Versus Power

in efficiency has been observed for throttle points TH6 and TH15.

Another notable performance variation, measured during the throttling tests, is the change of neutralizer flow rate margin to prevent plume mode operation. Neutralizer characterizations are performed at each throttle point, during the throttling tests. The flow rate of Xenon to the neutralizer is reduced in small increments to determine the flow rate at which the transition to plume mode occurs. Plume mode occurs when the cathode sheath extends to the anode, resulting in large voltage oscillations, an increase in neutralizer keeper voltage, and the production of energetic ions. These ions have sufficient energy to erode neutralizer surfaces, reducing the lifetime and performance of the neutralizer cathode. Plume mode can also trigger the set points of the recycle circuit, disrupting normal thruster operation. It is therefore desirable to know at which flow rate this transition occurs. The TH0 point has been operated closest to plume mode, as neutralizer cold flow loss is most significant at the lower power levels, reducing total thruster efficiency. TH15 has been operated with the largest margin from plume mode, as cold flow losses are less significant at the higher power levels. Over the first 5,000 hours, neutralizer margin decreased for TH0, 3, 9 and 12. From 5000 to 13,000 hours, the margin remained the same. From 13,000 to 15000 hours, the margin increased slightly, and remained the same through 19,000 hours. For TH 6 and 9, the flow rate margin has remained constant. During

routine sensitivity testing of FT2 at 22,000 hours of operation, it was discovered that margin from plume mode has been exceeded for the minimum power point. The observed keeper voltage exceeded 5 V peak-to-peak. The nominal TH0 flow rate is no longer sufficient to prevent plume mode onset. Overall the flow rate margin from plume mode has decreased from beginning of life values, for all but TH6 and TH9, with the most significant reduction at the TH0 throttle point.

Accelerator Grid Aperture Erosion

Photographs and video data of the accelerator grid are taken at regular intervals over the course of the test. They are taken at several different radial locations on the downstream face of the accelerator grid. Shown in Fig. 6 are photographs of the center hole of the FT2 accelerator grid from 125 to 21306 hours. In the photograph taken at 125 hours, the cusp from the grid manufacturing process can be seen; however, in the later photographs, the cusp has been eroded away. After 4693 hours of operation, a star erosion pattern is forming around the apertures and a regular pits and groove pattern is being eroded into the webbing between the apertures. Measurements of aperture diameter for four different radial locations are shown in Fig. 5. The measurements have an uncertainty of ± 0.025 mm. The dashed vertical lines indicate the start of a new test segment, and the corresponding power level is shown in between the vertical dashed lines. Data is plotted for diameter measurements taken at the

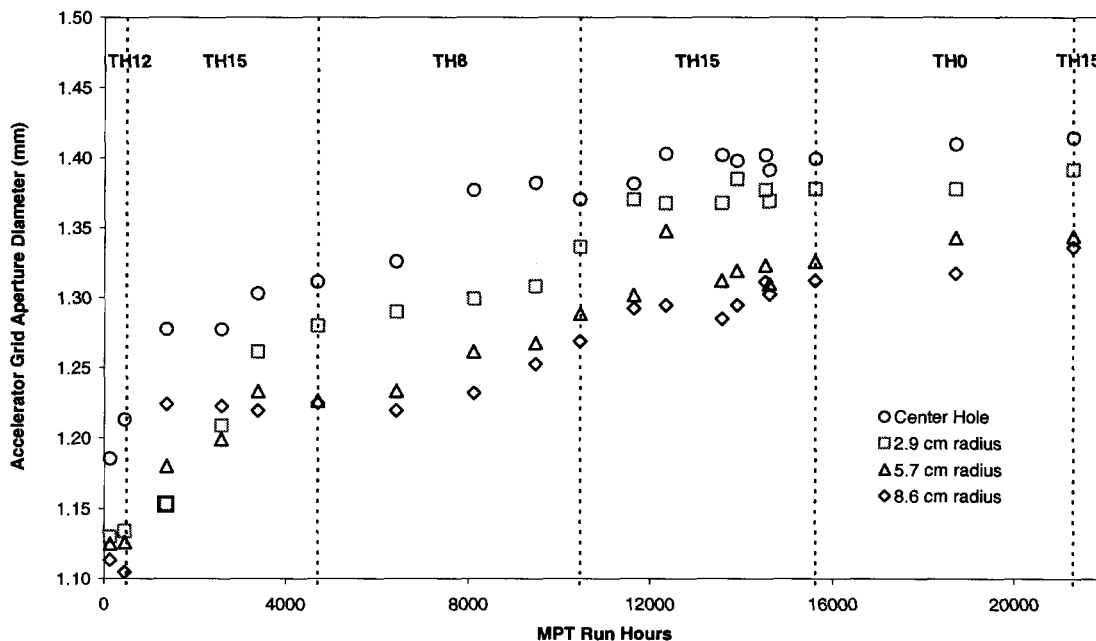
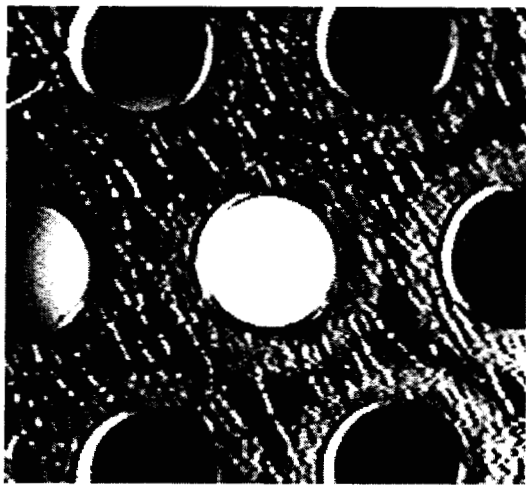
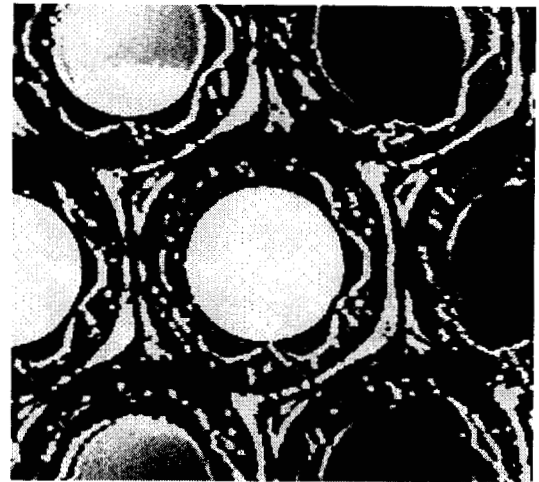


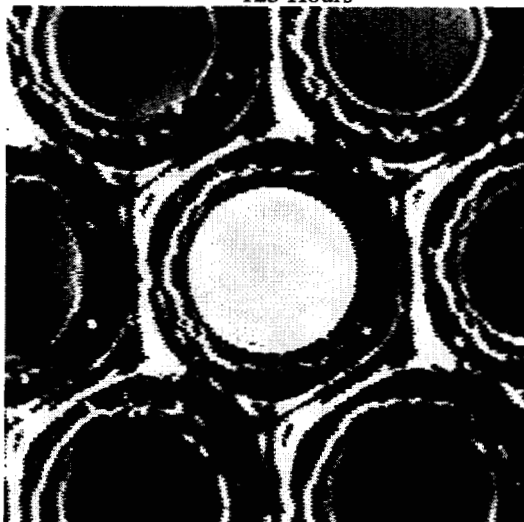
Fig. 5 FT2 Accelerator Grid Aperture Diameter for 5 different radial locations



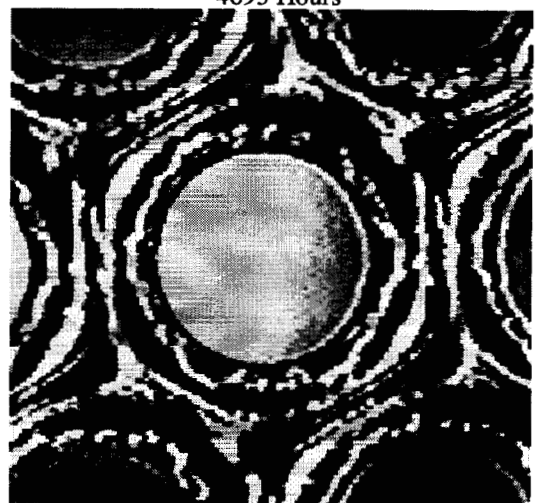
125 Hours



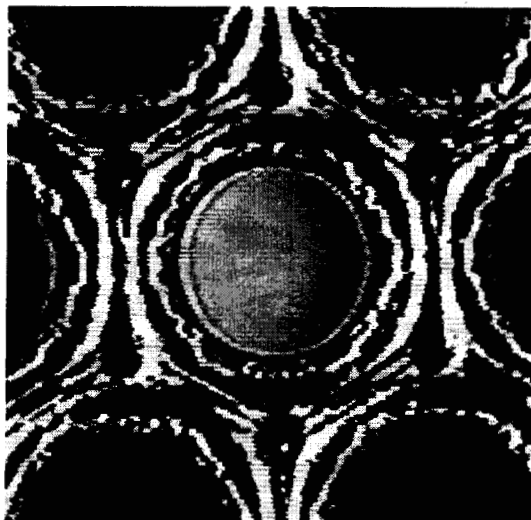
4693 Hours



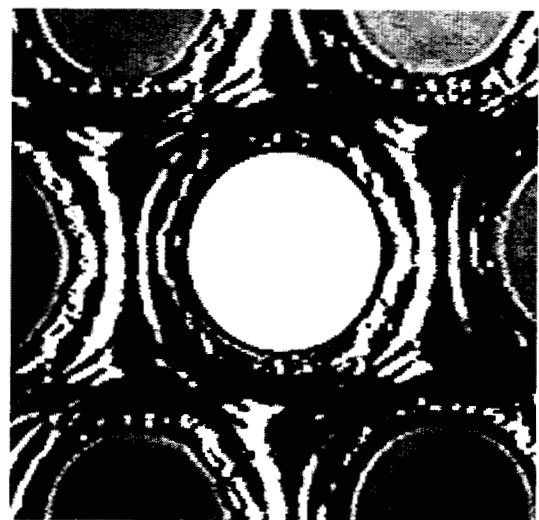
9473 Hours



15617 Hours



18706 Hours



21306 Hours

Fig. 6 FT2 Accelerator Grid Aperture Erosion at the Center Hole

center out to 8.6 cm from the center. For the first 5000 hours of FT2 testing, the center hole experienced the most substantial rate of erosion. The other three holes also experienced their highest enlargement rate during the first full power test segment. The rate of enlargement decreased for all four holes during the TH8 segment, and leveled off during the second full power segment. During the TH0 test segment, all holes exhibited a very low aperture enlargement rate. It is important to note, that there is a greater error in the measurements of the outer holes, as the grid is dished, and measurements are being made at a slight angle.¹⁰

A possible explanation for the differences in rates of erosion as a function of radial location and power level is the corresponding current density profile. Current density decreases monotonically with radius and as a result the aperture erosion also decreases with radius. In addition, at the higher power levels, where the beamlets are more focused, the profile is more peaked at the center. The near field faraday probe is used to measure this profile over the thruster throttling range. Fig. 27 is a plot of beam flatness versus input power. At TH15, the radial current density profile is 13% more peaked than at TH0. This may be a possible explanation for the lower erosion rate of the outer holes as compared to the center holes at TH15. Similarly at the lower power levels, the extracted beam current is lower, as is the current density, resulting in less aperture enlargement, as was seen during operation at TH0. The difference in the initial erosion rate (< 447 hours), however, may have been due to slight misalignment of the grids during the assembly process.

It is theorized that charge exchange ions are primarily responsible for the erosion on the upstream face of the accelerator grid. Charge exchange ions are formed when a fast ion collides with a slow neutral, resulting in the neutral giving up an electron to the fast ion. The product of the interaction is a fast neutral and a slow ion. The slow ion is then accelerated back onto the grid surface by the negative potential of the accelerator grid, eroding the surface in a predictable pattern. The pattern of the erosion of the FT2 accelerator grid has been computationally modeled in reference [11], and the charge exchange predictions correspond remarkably well to the FT2 erosion pattern. In addition, this suggests that the higher the density of neutrals in the vicinity of the downstream side of the accelerator grid, the greater the charge exchange production, and hence the greater the erosion. Therefore ground testing, with a much higher density of neutrals than space, due to the higher background pressure, may be a harsher environment for the thruster with regards to accelerator grid erosion.

Discharge Cathode Keeper Erosion

Photographs of the discharge cathode keeper electrode and orifice plate are shown in Fig 9. During the first 4693 hours, at full power, little discharge cathode keeper erosion was observed. The surface of the keeper was pitted, but the diameter of the orifice did not increase significantly. During operation from 4693 to 10451 hours, at TH8, the observed keeper erosion increased significantly, eroding the keeper plate, and exposing the cathode heater region. Full power operation resumed at 10451 hours, and the cathode keeper erosion continued, but at a slightly slower rate. At the end of the test segment, 15617 hours, the cathode heater wire was fully exposed. Operation at the minimum power point (TH0), 15617 to 21306 hours, did not result in any significant cathode keeper erosion or orifice diameter change. Fig. 7 is a plot of keeper inner orifice diameter over time.

The exact cause and conditions that brought on the discharge cathode keeper erosion are not fully understood at present. Although, the first observation of increase in the rate of erosion coincided with an intermittent short between cathode keeper to cathode common, that occurred at approximately 5850 hours. The voltage between the cathode keeper and cathode common is monitored during thruster operation; typically it is 3 to 5 V. The intermittent short caused the cathode keeper voltage to jump from 3.5 V to ~0.4 V. At 8,873 hours the cathode keeper-cathode common short cleared when the cathode keeper orifice eroded sufficiently. The erosion, however, did proceed beyond this, until the end of the second TH15 segment, at 15617 hours.

One possible mechanism for the observed keeper erosion is the increase in the production of multiply charged xenon ions at the half power point, due to a low nominal cathode flow rate, as compared to the 0.5 and 2.3 kW operating points. For a fixed maximum space charge current limit from the cathode, if the effective xenon flow rate is lowered, the charge of the xenon ions must increase.⁹ Multiply charged xenon ions have sufficient energy above the sputter threshold of the keeper material to allow for severe sputtering of the surface. Measurements of the double to single ion content of the beam indicate that the TH8 operating point has a proportionately high doubles content. In addition, in the vicinity of the cathode assembly, there is a relatively strong magnetic field, increasing electron residence time, and therefore ionization probability. Due to the enlargement of the orifice, for a constant flow, the xenon density in the orifice is decreased. Therefore when full power operation was resumed, the xenon density was lower and multiply charged ion

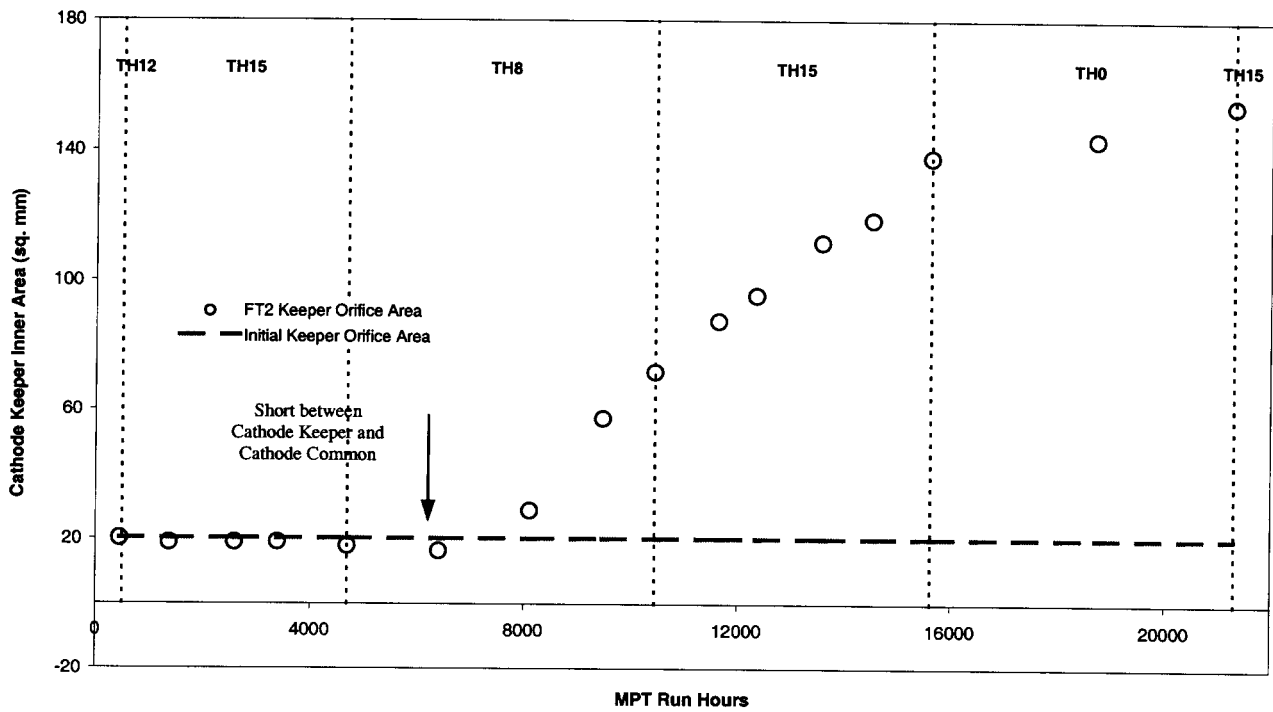


Fig. 7 FT2 Cathode Keeper Orifice Area

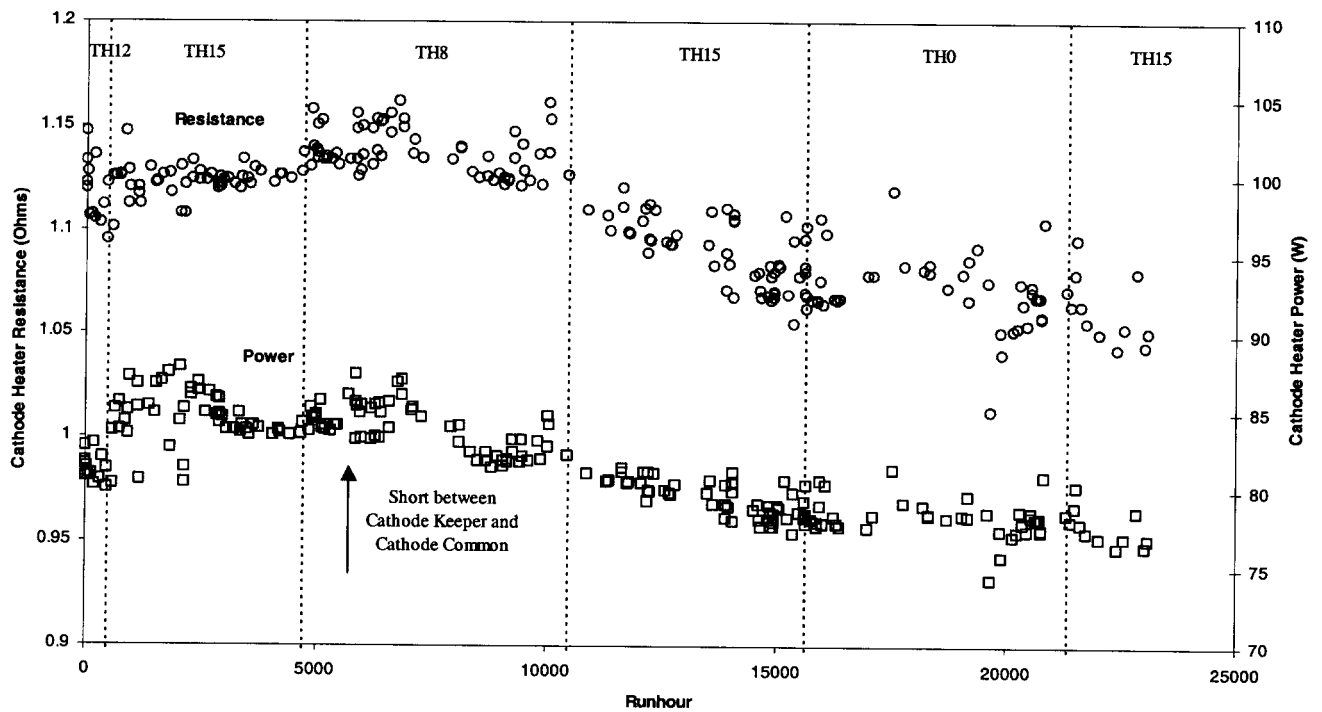
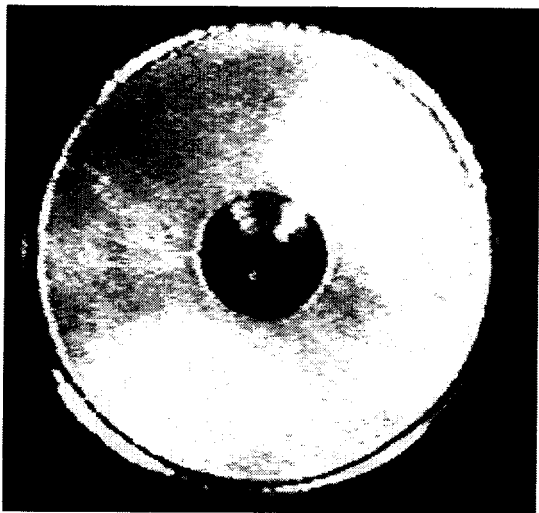
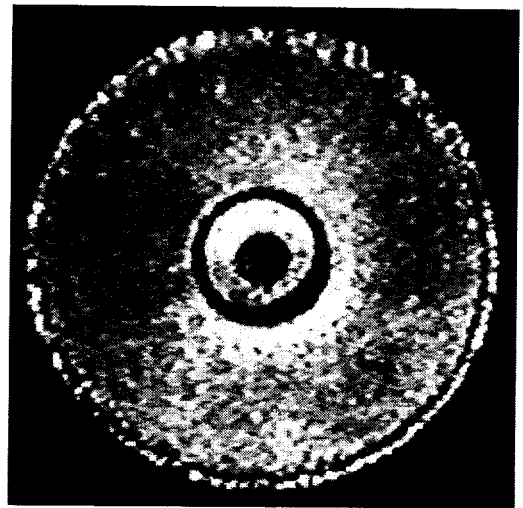


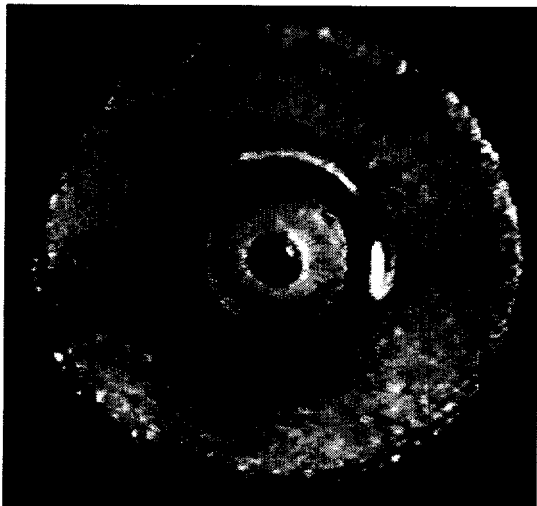
Fig. 8 FT2 Cathode Heater Resistance and Power



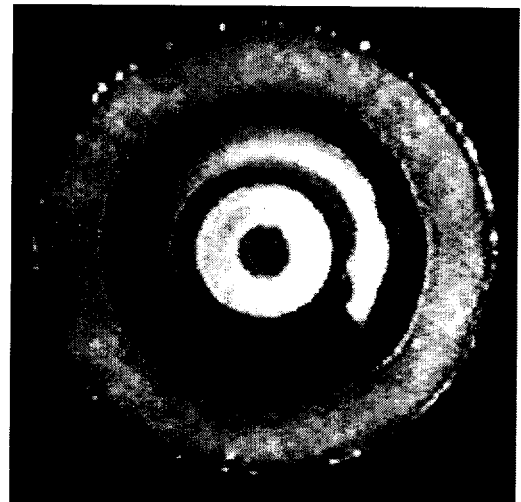
0 Hours



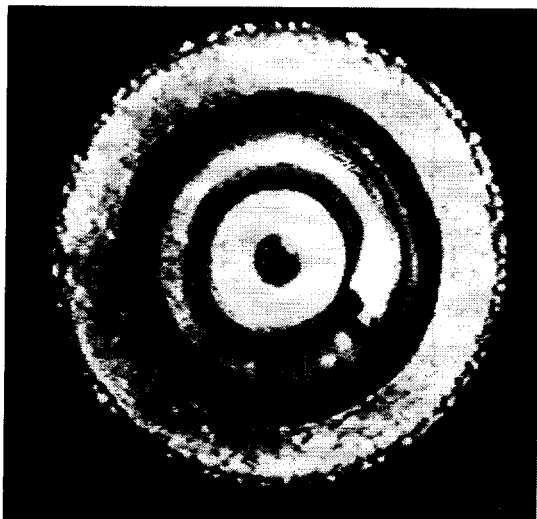
4693 Hours



10451 Hours



15617 Hours



18706 Hours



21306 Hours

Fig. 9 FT2 Discharge Cathode Keeper Photos

production increased, resulting in the continued keeper erosion seen during the second TH15 power segment.

In addition to the visual erosion of the keeper surface first observed at ~5000 hours, the discharge cathode heater power and resistance have been decreasing at a steady rate, as is shown in Fig. 8. As the keeper open area has increased, increased radiation from the open area may be responsible for the reduced power. Or it is possible that the eroded keeper material is depositing on the heater or heater wiring reducing the effective resistance of the heater. As of 23,000 hours, the heater power has been reduced by ~6 W from its average beginning of life value. This is critical, because sufficient heater power is required to overcome the work function of the cathode insert, enabling electron emission. The onset of degradation in heater power and resistance also coincides with the cathode keeper to common short, and the increase in discharge keeper erosion. The heater power continued to drop, however, after the short was cleared. Prior to the short, from 447 to 5500 hours, the discharge heater resistance was exhibiting a slight increase with time, a phenomena also occurring with the neutralizer heater to the present day. The reason for this increase is not known.

In spite of this severe discharge keeper erosion and heater power reduction, the ability to ignite the discharge cathode has not been affected. This suggests that sensitive cathode heater components have not been damaged, and this erosion mechanism is not expected

to cause thruster failure in the near term.

Ion Optics Performance

Performance measurements of the ion accelerator system are taken every 100 to 200 hours of normal operation. The key performance parameters for ion thrusters include the screen grid's transparency to ions, perveance limit, and the electron backstreaming limit. The ability of the ion accelerator system to extract and accelerate ions is a key performance limiter with regards to optimization of Isp and thrust. The perveance limit is by definition the maximum current that can be extracted by a pair of electrodes in the space charge limit.²⁰ With regards to ion thrusters, is it the measure of how defocused the beam can be before direct ion impingement on the accelerator grid occurs. The beam is de-focused by gradually lowering the screen grid voltage. Direct ion impingement can lead to rapid accelerator grid erosion, as the impacting ions are accelerated through the total voltage applied between the grids. Fortunately, this is a controllable wear mechanism as screen grid voltages are maintained with sufficient margin above the perveance limit and below the cross-over limit. For the ground tests, the perveance limit is defined as the screen grid voltage where a 1 V reduction is screen voltage, results in a .2 mA increase in accelerator grid impingement current. At the other end of the spectrum is the cross over limit. The cross over limit is where the over focused ion beamlets converge, and the upper and lower portions cross over, also resulting in impingement current on the accelerator grid. Although the cross over limit is not measured

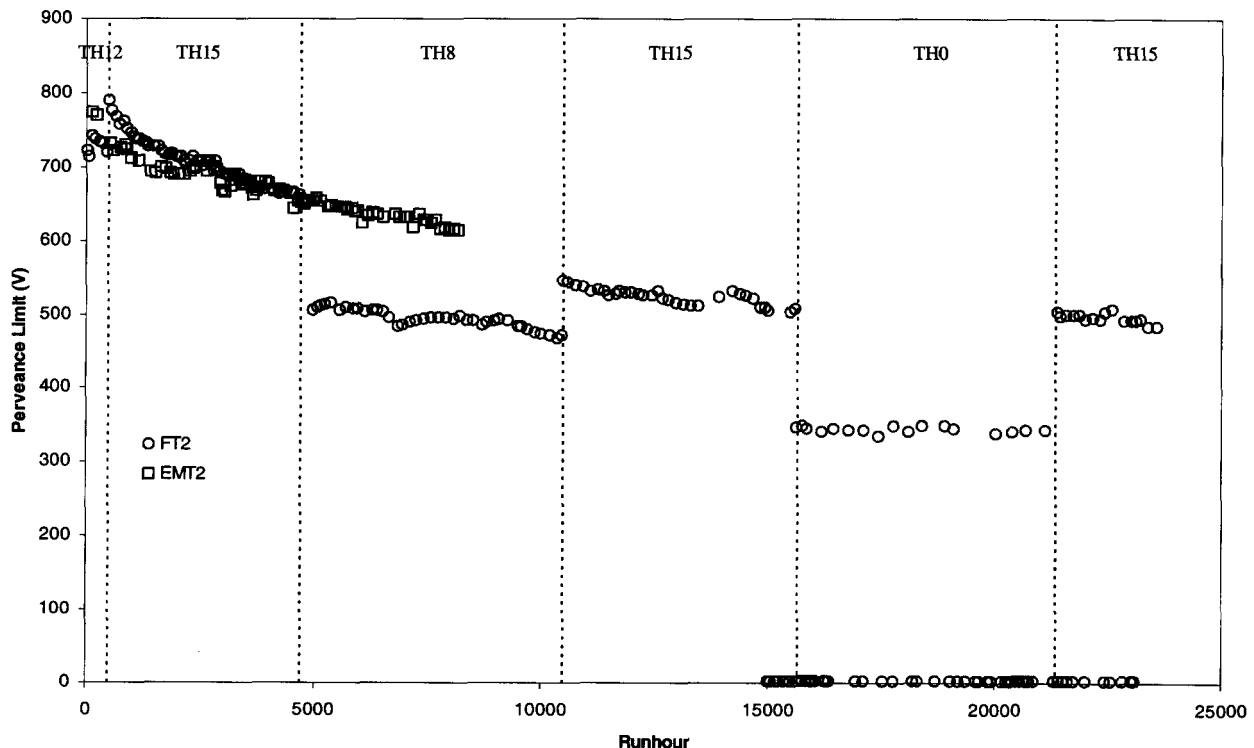


Fig. 10 FT2 and EMT2 Perveance Margin

during this test, the accelerator grid current is recorded every 5 seconds by the monitoring system. Inadvertent operation of the thruster at either of these two limits will trigger the monitoring program to automatically shutdown the thruster and put it in a safe mode.

Fig. 10 shows the change in perveance limit over the course of the test. For EMT2, the perveance limit decreased at the fastest rate during the first 1000 hours. Similarly, the FT2 limit decreased most significantly at the start of the first TH15 test segment. As the thruster wears, the accelerator grid holes enlarge, and as a result the beam must become more de-focused for ions to impinge on the accelerator grid. Therefore as the thruster wears, the perveance limit decreases. As accelerator grid wear decreases with power level, the TH8 and TH0 test segments showed a less significant increase in perveance limit with time.

When operating FT2 at TH15, the perveance limit initially was lower than that of EMT2. But by 2500 hours and until the end of the first FT2 full power test segment, the perveance limits for both thrusters are virtually the same. A shift prior to 124 hours is also noted in the perveance limit data for FT2.²

In addition to focusing and accelerating ions, the ion

optics also prevents beam-neutralizing electrons from backstreaming into the discharge chamber. Electron backstreaming occurs when the potential at the center of the accelerator grid apertures is not sufficiently negative to prevent electrons from streaming into the discharge chamber. Electrons backstreaming into the discharge chamber are indistinguishable from ions being accelerated out of the thruster, to the beam power supply. As the beam current is held constant, an increase in electron current will result in a decrease in ion (positive) current or discharge current, significantly reducing thruster performance.

The electron backstreaming limit is determined by increasing the accelerator grid voltage until the discharge loss begins to decrease. Discharge loss is the ratio of energy cost of producing beam ions to the extracted beam current. As stated previously, when backstreaming occurs the positive ion current extracted from the discharge chamber must decrease to maintain the beam current at the set point. As a result, fewer ions are produced in the discharge chamber and the discharge loss decreases. For FT2 testing, the electron backstreaming limit is defined as the accelerator grid voltage at which the discharge loss decreases by 1%. The backstreaming limit is a life-limiting factor for ion thrusters. If the backstreaming limit exceeds the voltage

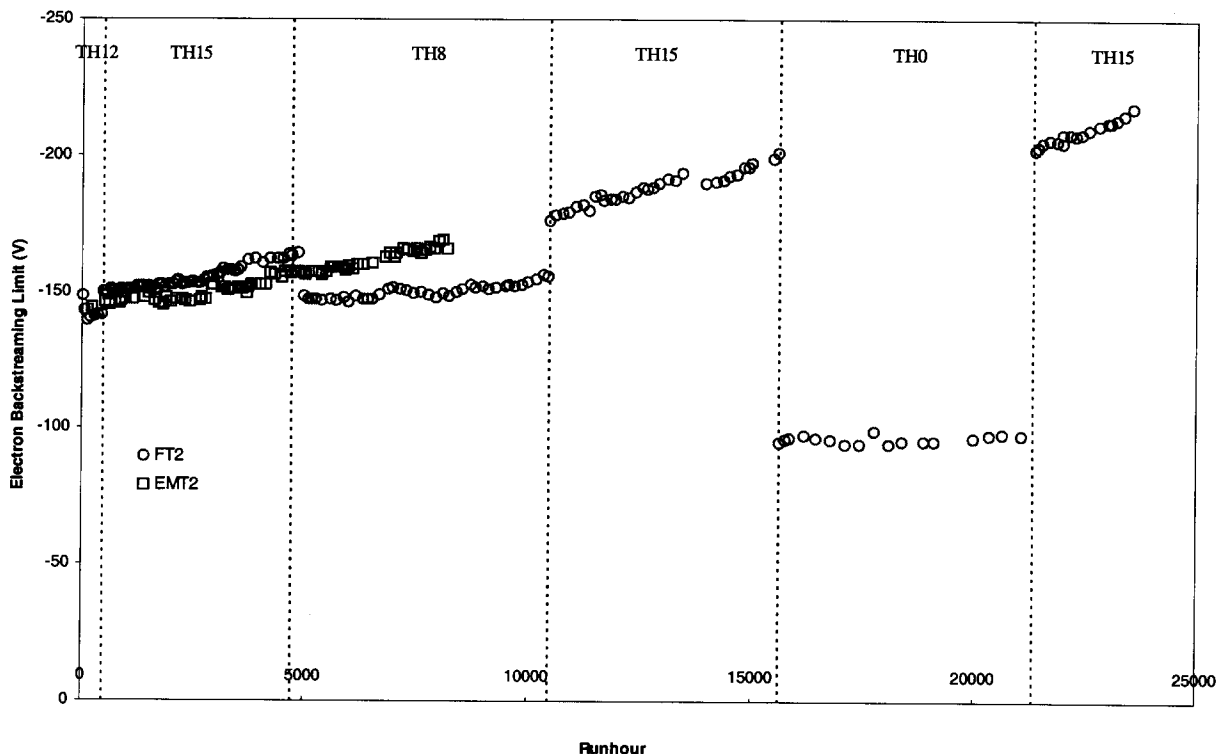


Fig. 11 FT2 and EMT2 Electron backstreaming Limit

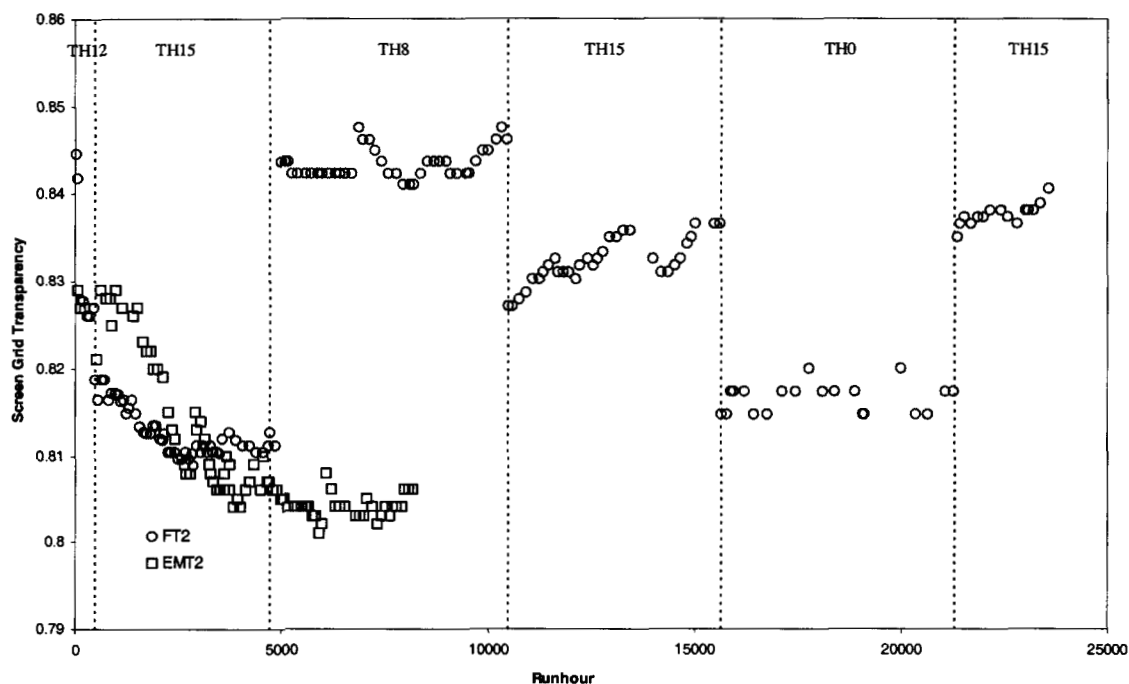


Fig. 12 FT2 and EMT2 Screen Grid Transparency

capability of the accelerator power supply, backstreaming cannot be prevented, resulting in thruster failure. The electron backstreaming limit is a function of the voltage of the accelerator grid, aperture size, ion current extracted through the apertures, spacing between the grids, and is most likely to occur near the center, where the beam current density is maximum. As the accelerator grid apertures enlarge as the thruster wears, a more negative accelerator voltage is needed to maintain a center hole potential sufficiently negative to repel electrons. The charge exchange ions, discussed previously, are directly accelerated by the potential of the accelerator grid. Therefore, as the accelerator voltage is made more negative, the energy of the impinging ions increases, and aperture erosion increases. Therefore it is desirable to minimize the voltage applied to the grid, while at the same time preventing electrons from backstreaming.

A plot of the electron backstreaming limit for EMT2 and FT2 is shown in Fig. 11. A significant shift in the electron backstreaming limit occurred over the first 124 hours of FT2 testing. Another shift occurred between 13,467 and 13,993 hours. These shifts may be due to an increase in the spacing between the screen and accelerator grid, thereby lowering the intra-grid electric field strength. Although the design grid spacing at ambient temperatures should not change over time, it is possible that the presence of back-sputtered carbon deposits on the accelerator grid, can alter its thermal

emissivity, changing its steady state temperature. This would result in a different hot-gap spacing when the thruster is running. This may account for the initial shift in the electron backstreaming limit. The second shift occurred following an unusually long exposure to a higher background pressure. Oxygen and water vapor present in the chamber, may have reacted with the carbon deposits, resulting in an additional change in its thermal emissivity.

Comparison of the FT2 and EMT2 electron backstreaming limit indicates a more negative limit for FT2. The 6 V difference is thought to be due to a slight difference in the manufactured grid gap of the two thrusters. This is likely, as reference [11] indicates that a difference in grid gap less than the manufacturing and assembly tolerances of EMT2 and FT2, would result in the difference measured in the ground tests.¹¹

From Fig. 11, it is also clear that the electron backstreaming limit is less negative for TH12, TH8 and TH0, as compared to the TH15 power level. The apparent jumps in electron backstreaming limit at the different test segments are due to differences in beam current extracted through ion optics apertures. As the power level increases, beam current increases, as does the positive space charge. As a result the potential in the apertures increases, requiring a more negative accelerator grid voltage to prevent electron

backstreaming. The increase in backstreaming over a specific test segment is likely due to accelerator grid aperture enlargement, which is most significant at the higher power levels. At TH0, aperture enlargement is minimal, and the backstreaming limit remained constant.

Screen grid transparency to ions is a measure of how effectively ions are extracted from the discharge chamber. The measurement is made by biasing the screen grid negative of cathode potential to repel discharge chamber electrons. The total beam current and current to the screen grid is then measured. The ratio of ion current extracted through the grid to the total current is the transparency. Fig. 12 shows the transparency measured over the course of the test. The trend is an increase in screen grid transparency over time, due to the enlargement of screen grid apertures. This effect is most noticeable at the higher power levels.

The shift mentioned previously in the electron backstreaming limit, over the first 124 hours of FT2 testing, is also noted in the transparency data. After this initial shift in screen grid transparency, the transparency measured at TH12 on FT2 and at TH15 during EMT2 testing was comparable. At full power the FT2 screen transparency was less than that of EMT2 up to about 2500 hours. After about 3000 hours, the screen grid transparency for FT2 at full power was slightly higher than that for EMT2. The reason for these differences at full power is not known; however, they may be due to small differences in grid spacing between the two thrusters. After throttling to TH8 the transparency was higher than that observed at TH15 or TH12 after the shift during the first 124 hours of FT2 testing. The transparency remained relatively constant during operation at TH8. When full power operation was resumed at 10,451 hours the screen transparency was higher than during the first full power segment. During the second full power segment the FT2 accelerator grid was biased more negative than during the first full power segment. This results in a stronger electric field between the grids, which facilitates ion extraction—hence the higher screen grid transparency. The screen grid transparency remained relatively constant during the TH0 test segment. This is to be expected, as little change in the grid aperture size occurs at the lower power levels.⁶

Although the observed transparency differences over the course of the test are minor, they do affect discharge chamber performance. A reduction in transparency requires a higher production of ions, to maintain the same beam current. Higher ion production requires more power, thereby reducing thrust efficiency.

Discharge Chamber Performance

Figures 13 and 14 show the cathode and main flow rates over the past 23,000 hours of operation for both FT2 and EMT2. During the initial full power segment it can be seen that the FT2 main and cathode flow rate is lower than EMT2. The discrepancy in flow rates was due to a calibration error in the FT2 flow system, only discovered after 3780 hours of operation. In addition, the main flow controller on FT2 also drifted an additional 1% between 2000 and 2350 hours, due to changes in ambient temperature. Lower main and cathode flow increases propellant utilization efficiency, improving overall thruster efficiency, but also increases the double ion content of the beam, which can lead to increased sputter erosion of thruster surfaces. As operation at the lower flow rates did not have any notable effect on thruster performance or wear during these first 3780 hours of operation, it was decided to leave the flow rate as is, to benefit from the improved mass utilization.

Another flow calibration error occurred from 19,000 to 19500 hours. Incorrect calibration constants were entered into the flow system resulting in an increase in main and cathode flows. The effect of this flow increase is quite visible in figures 16 and 17, plots of discharge current and voltage. After the error was corrected discharge chamber performance parameters returned to nominal levels.²

Figure 15 shows the trend to increasing discharge current with time during the first test segment, at TH15. A possible explanation of this trend is that increasing accelerator grid aperture size, leads to increased neutral xenon loss, lowering the neutral density in the discharge chamber. As beam current is fixed, and proportional to neutral density and discharge current, a decrease in neutral density would result in an increase in discharge current.

During operation at TH8, the half power point, the discharge current decreased approximately 0.68 A, over 5509 hours of operation. The cause for this decrease is not known at this time, although this rate of decrease does correspond to the short that developed between the cathode keeper to cathode common, resulting in a 3 volt drop in cathode keeper voltage. The rate of discharge voltage increase rose over this interval until the discharge current became relatively constant.

Operation at the full power point resumed over 10455 to 15617 hours. At the start of this test segment, the discharge current was 0.38 A higher than the end value at the previous full power segment. At the start of this test segment, the discharge current was 0.38 A higher than the end value at the previous full power

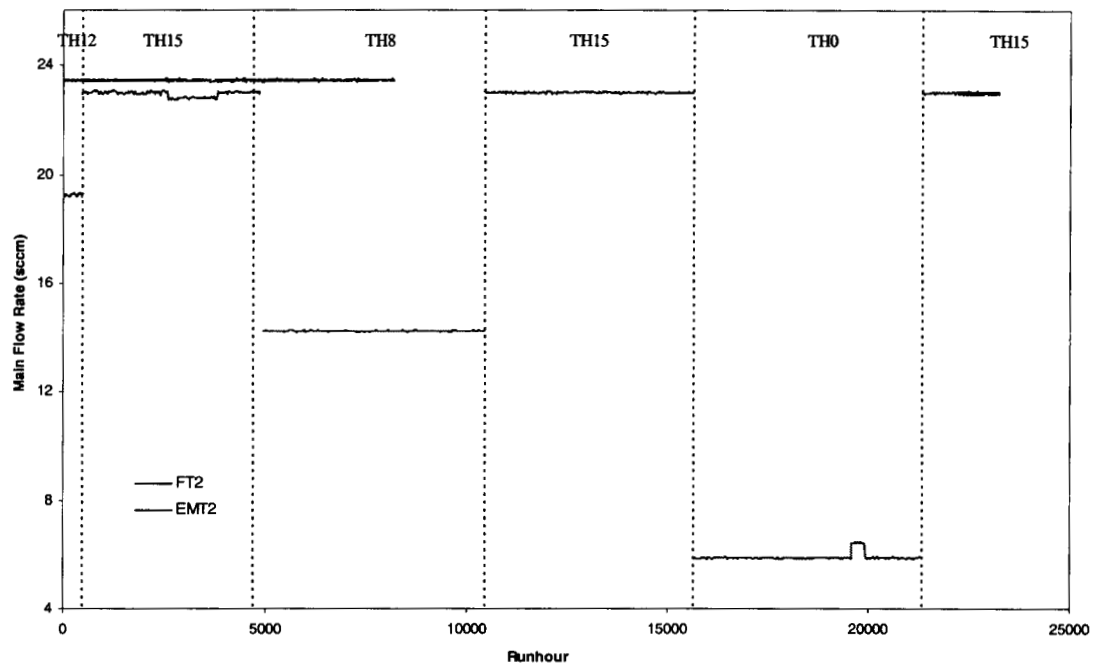


Fig. 13 Main Flow Rate Comparison for FT2 and EMT2

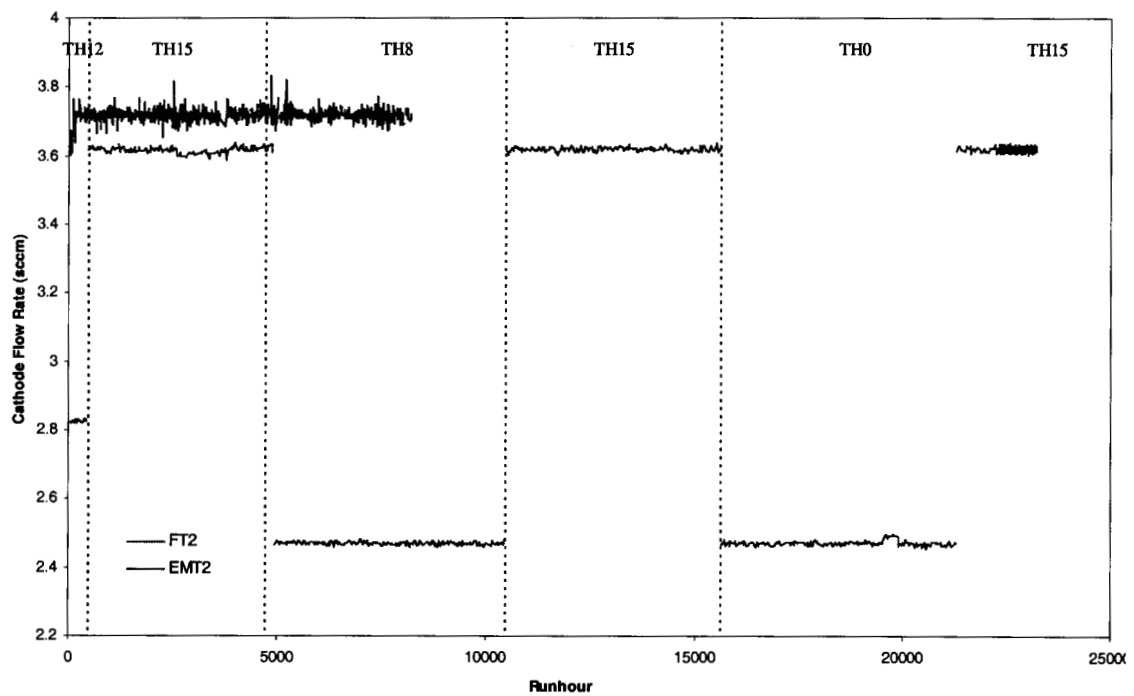


Fig. 14 Cathode Flow Rate Comparison for FT2 and EMT2

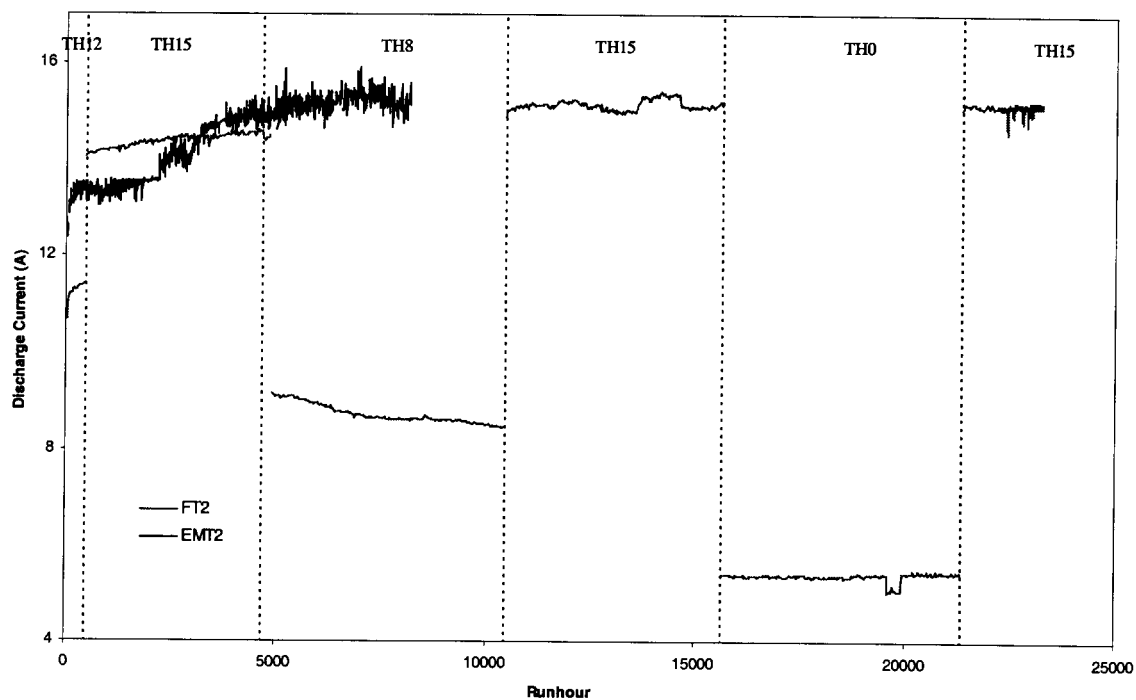


Fig. 15 Discharge Current Comparison for FT2 and EMT2

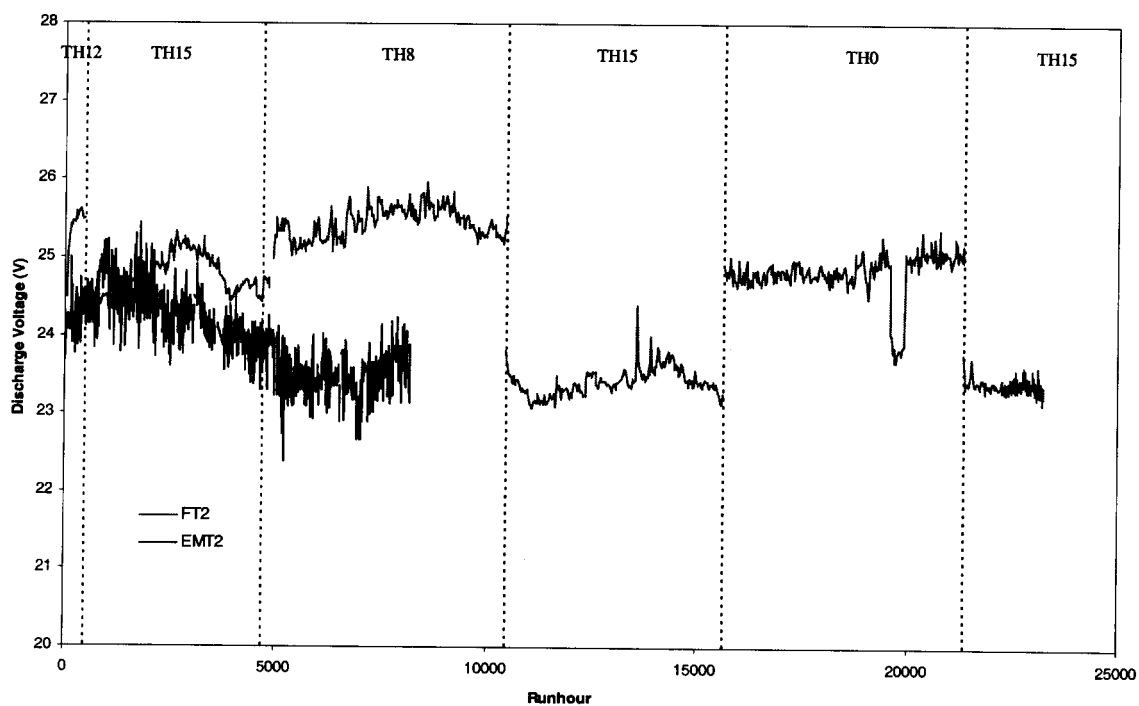


Fig. 16 Discharge Voltage Comparison for FT2 and EMT2

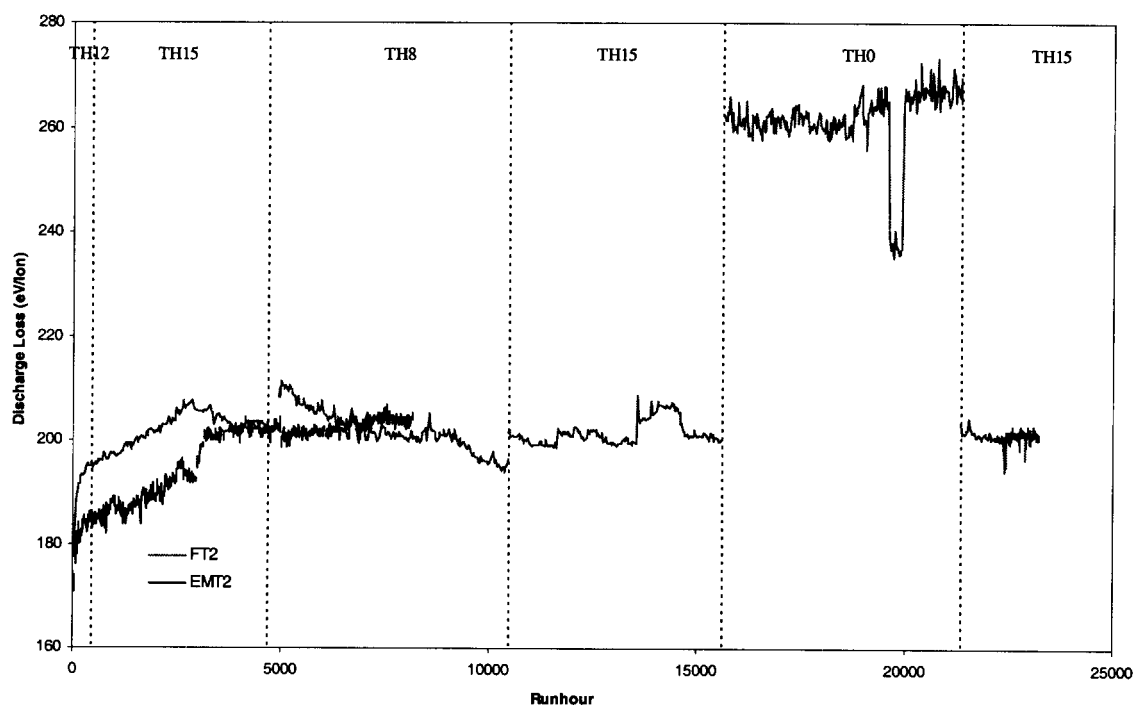


Fig. 17 Discharge Loss Comparison for FT2 and EMT2

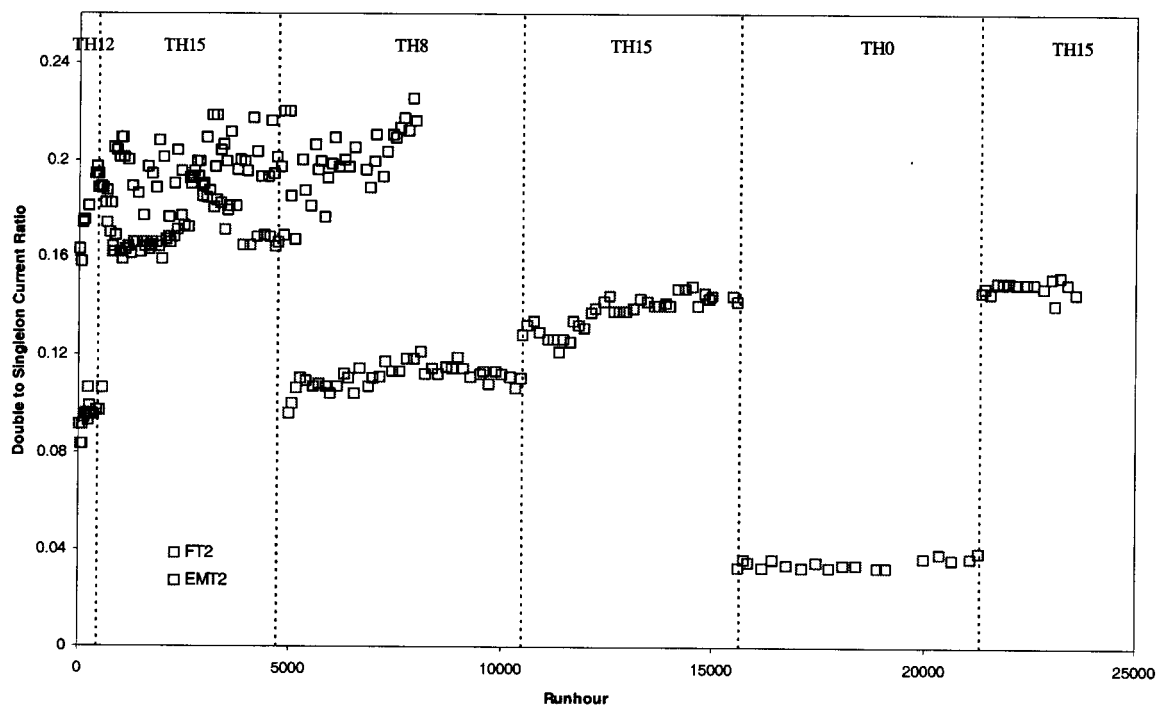


Fig. 18 Double to Single Ion Content Ratio Comparison for FT2 and EMT2

segment. During this interval the discharge current increased 0.28 A, corresponding to a lower rate of neutral loss. Operation at TH0 showed virtually no change in discharge current over its 5663-hour interval. This corresponds to the absence of accelerator grid enlargement at this power level.

A comparison of the discharge loss for EMT2 and FT2 is shown in Fig. 17. It is seen that the discharge loss for FT2 is higher than that for EMT2 until the discharge current became lower for FT2 than EMT2 at 3000 hours. Following that, the discharge loss for FT2 decreased as the discharge voltage decreased. After 4000 hours the discharge losses for both thrusters, operating at full power, coincide even though the discharge currents and discharge voltages are slightly different for the two thrusters. After throttling FT2 to TH8, the discharge loss increased about 8 eV/ion and then slowly decreased back to a level slightly lower than that observed during operation at full power. The FT2 discharge loss during the second full power segment is comparable to that during the first full power segment, even though the discharge current and voltage were slightly different for each of the segments.

The double-to-single ion current ratio is an important parameter directly related thruster performance and wear. Doubly charged ions are more energetic and hence can sputter erode discharge chamber surfaces. Sputtering can lead to material degradation as well as the production of loose particulate matter (flakes) that can lodge between the grids and potentially cause a short. Additionally, it takes almost twice the energy to create a doubly charged Xenon ion, reducing power efficiency. Although the Isp is increased by a factor of $\sqrt{2}$, the thrust is reduced by a factor of $1/\sqrt{2}$, for double ion current. This is unacceptable for low thrust devices, such as ion thrusters.

The double-to-single ion current ratio is shown in Fig. 18 for FT2 and EMT2. The variation between the EMT2 and FT2 doubles ratio is thought to be primarily due to the alignment of the FT2 ExB probe. At the start of FT2 testing, the ExB probe was initially aligned to provide maximum single ion current. However due to the shift in the ion optics observed after 124 hours of operation, it is likely the probe is no longer in the location of maximum singles current, resulting in a reduction of the measured doubles current for FT2. In addition, the probe used for EMT2 testing accepted more ions than the FT2 probe. This would further increase the measured double-to-single ion ratio, for EMT2, if a higher percentage of the doubles were produced near the thruster centerline.

During the first FT2 test segment, at TH15, the doubles ratio peaked at approximately 2500 hours, and then returned to the level at the beginning of the test segment. After reducing the FT2 power level to TH8, the double-to-single ion ratio exhibited a minor increase on the order of one percent. During the second TH15 test segment, the doubles ratio increased; roughly two percent increase over 5000 hours. During the TH0 test segment, the doubles ratio remained constant, at approximately four percent. Comparison of operation at the TH0, 8, and 15 operating points, also indicates a decreasing doubles ratio with decreasing power. However, there was only a two percent reduction from TH15 to TH8 operation, suggesting at proportionately high doubles content at TH8. This is most likely due to the comparatively lean discharge cathode flow rate at the TH8 operating point.

Neutralizer Performance

The neutralizer cathode is the source of beam neutralizing electron current to prevent spacecraft charging. Similar to the discharge cathode, the neutralizer is a hollow cathode, with neutral xenon gas flowed through it, inside a cylindrical keeper electrode (anode). The keeper serves two functions, to ignite the cathode during engine start, and to prevent the neutralizer cathode from extinguishing during recycle events, when the high voltage power supplies are cycled off and on. The keeper power supply maintains the neutralizer current at the fixed level specified in the throttle table. The neutralizer keeper voltage is dependent on the flow rate of xenon through the cathode, and the keeper current.

The neutralizer flow rate for FT2 and EMT2 is shown in Fig. 21. At the start of the EMT2 test, the full power neutralizer flow rate was set at 3.0 sccm. Although there was enough margin to avoid plume mode operation at full power, the neutralizer flow rate was increased when the DS1 xenon flow system was designed with the discharge cathode and neutralizer flow rates nearly matched [15, 16]. The higher neutralizer flow rates used in the DS1 flow system are also being used for FT2. The drop in neutralizer flow at ~19,000 hours was due to a flow calibration constant error, and was corrected in the data system shortly after. The neutralizer keeper voltage for FT2 and EMT2 is shown in Fig. 19. The keeper voltage for FT2 is lower than EMT2 at the full power point. This is due to the higher neutralizer flow to FT2 as discussed above. The spikes in the neutralizer keeper voltage for both engine tests correspond to times when the both cathodes are conditioned following cryopump regeneration. Cathode conditioning is a process where cathode heater current is applied at various levels to burn off surface contaminants that may deposit/absorb on the cathode

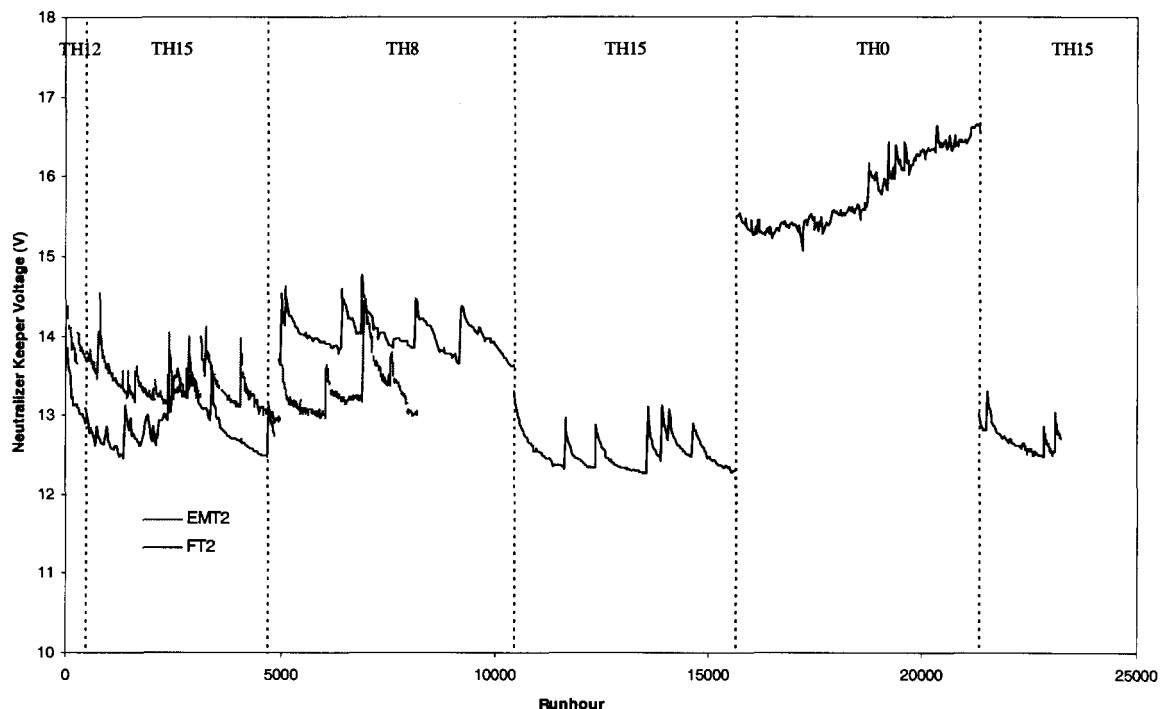


Fig. 19 Neutralizer Keeper Voltage Comparison for FT2 and EMT2

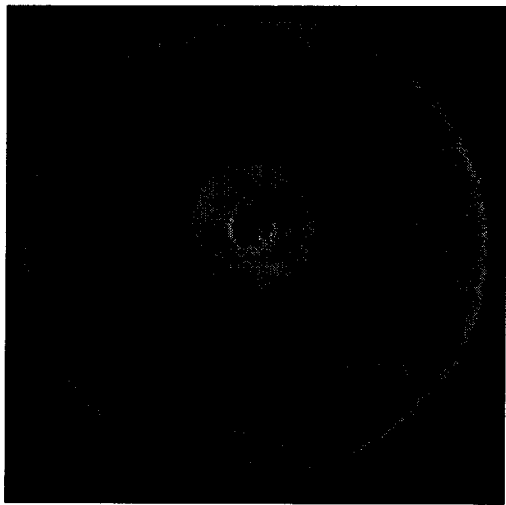
surface during exposure to the higher tank pressure, during cryopump regeneration.

An interesting trend was observed during operation at TH0, the minimum power point. The neutralizer voltage began to steadily increase over that 5000-hour test segment. This trend was not observed during the TH15 or TH8 test segments. Further inspection of photographs of the neutralizer orifice during this test segment reveals the formation of deposits within it, reducing its effective area. This will be discussed in more detail shortly. Additionally, when the thruster returned to full power operation after 21,306 hours, the neutralizer keeper voltage returned to its nominal operating voltage, showing no signs of the previous test segments rate of increase.

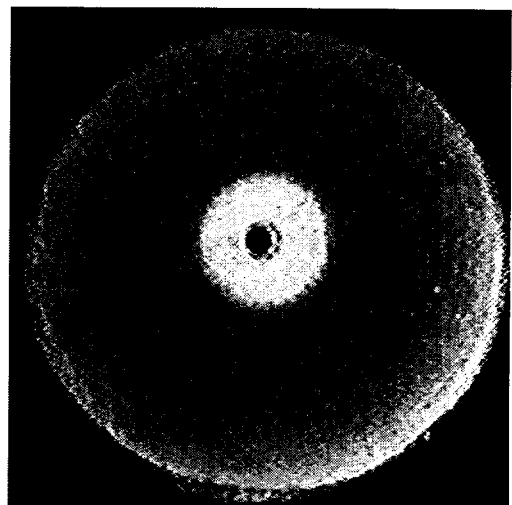
The keeper voltage is also an indication of how near the neutralizer is to operating in plume mode. Nominal operation of the neutralizer is called spot mode, where the voltage oscillations of the keeper are significantly less than 5 V peak-to-peak. As discussed previously, plume mode operation results in the production of more energetic ions that can erode neutralizer surfaces. Visually, it appears as an expanded, slightly flickering plume from the neutralizer. Operating at sufficient flow rate and current level for the specific throttle point can prevent plume mode operation. For FT2 testing, plume

mode operation is defined as a neutralizer keeper oscillation of greater than 5 V peak-to-peak. The peak-to-peak voltage trace of the neutralizer keeper is monitored on an oscilloscope continuously during FT2 testing. The trend has been a decreasing flow rate margin from plume mode operation, with the most significant reduction at the TH0 throttle point.¹⁵

Fig. 20 is a set of photographs of the neutralizer keeper and orifice, backlit by its heater. These images are used to monitor any neutralizer keeper erosion, and to measure the change in orifice diameter over time. During operation at the first full power segment no noticeable erosion of the keeper was observed, however a small reduction in orifice diameter was observed. Operation at TH8 and the second full power test segment did not result in any further keeper erosion and the rate of orifice change was minimal. During operation at TH0, the minimum power point, significant deposition of material began to form within the orifice. It is not possible to determine the exact location of these deposits, whether they are in the downstream or upstream end of the orifice, from the images. Fig. 22 is a plot of the orifice diameter over time. By the end of 21,306 hours of operation, the measured area of the orifice is 40% of the initial size. This phenomenon is the most probable cause of the increasing neutralizer keeper voltage also observed during operation at TH0.



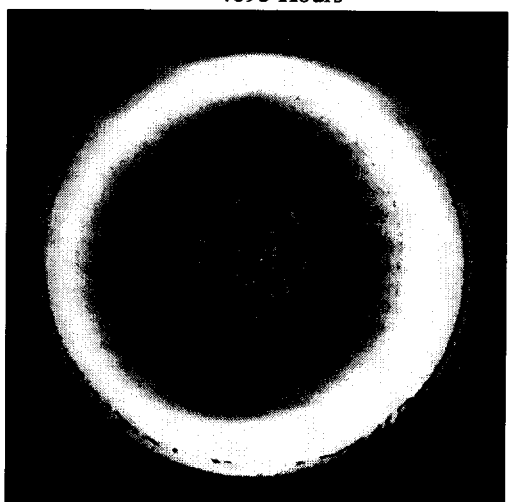
447 Hours



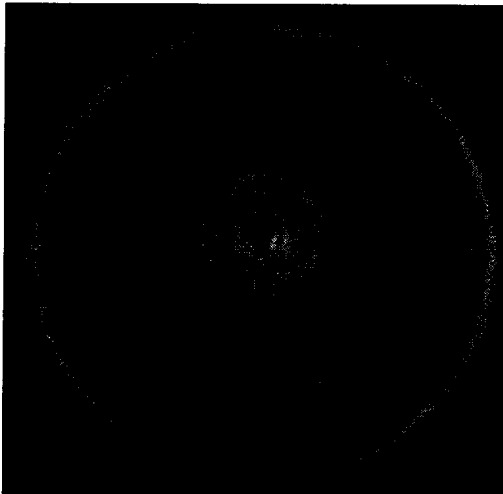
4693 Hours



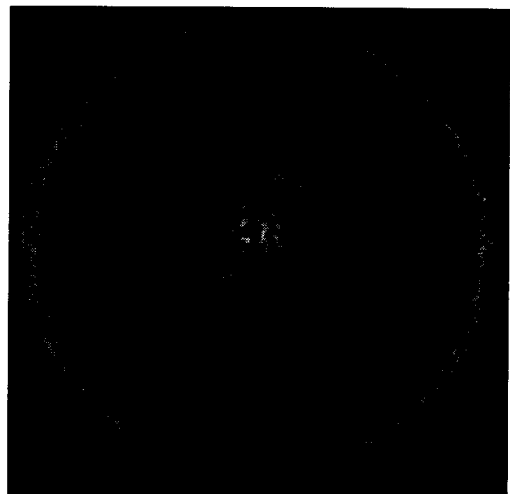
10451 Hours



15617 Hours



18706 Hours



21306 Hours

Fig. 20 FT2 Neutralizer Cathode Photos

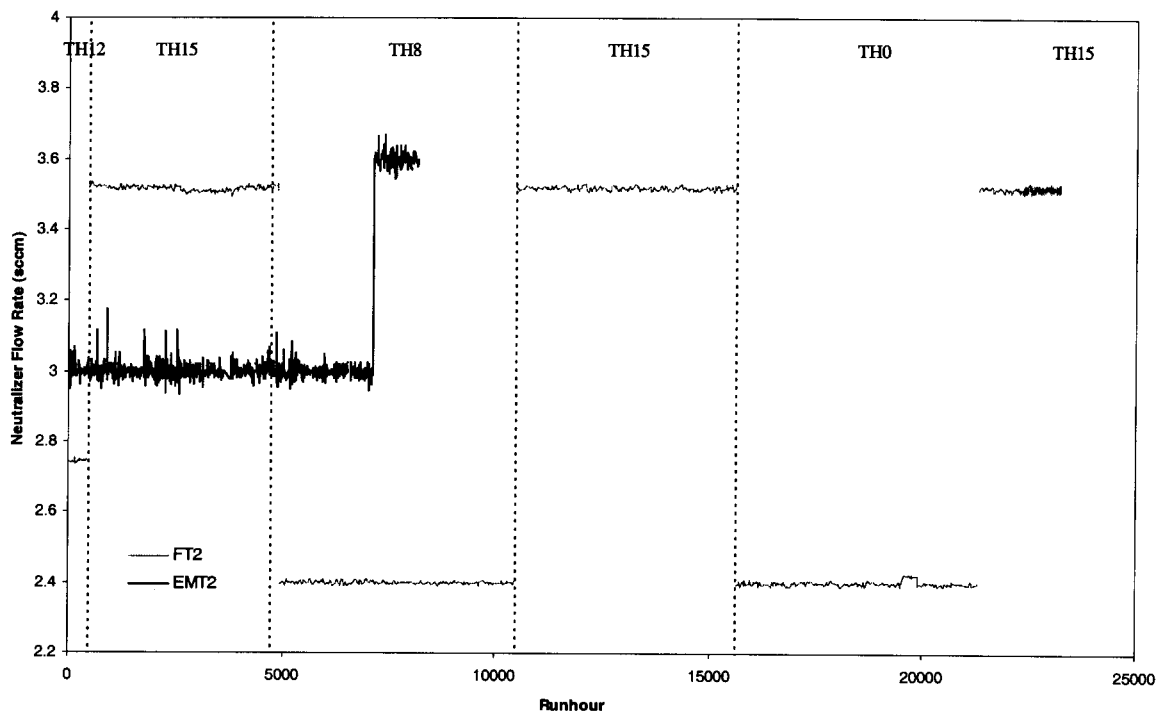


Fig. 21 Neutralizer Flow Rate Comparison for FT2 and EMT2

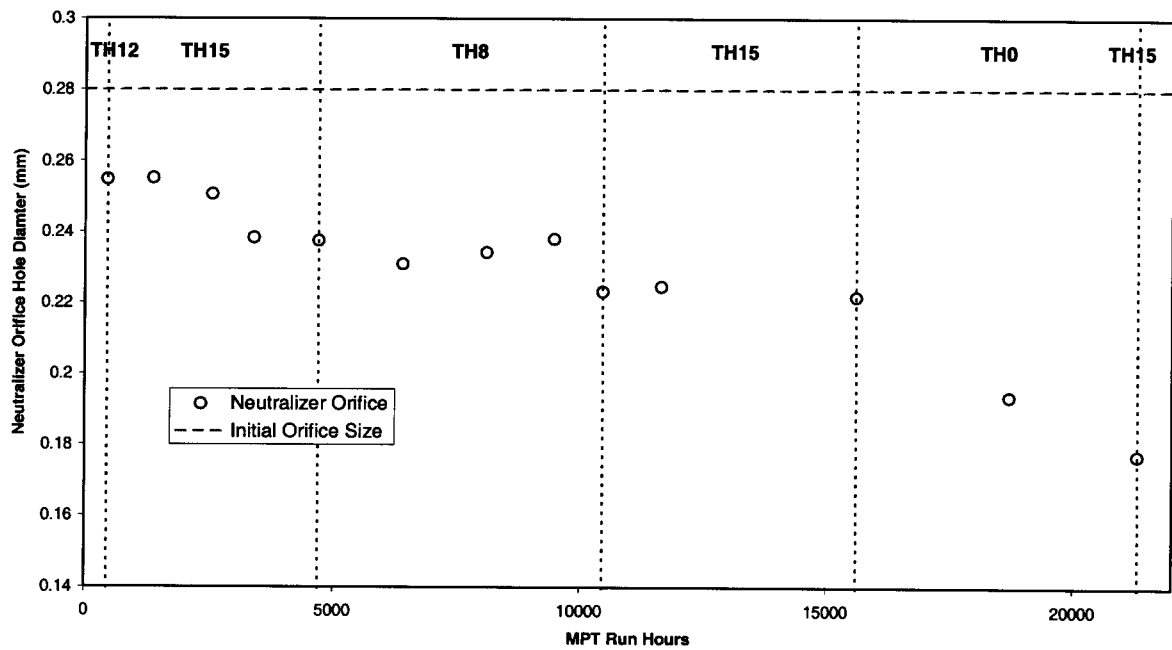


Fig. 22 FT2 Neutralizer Cathode Orifice Diameter

The deposition mechanism and composition are not known at this time. Analysis of the EMT2 neutralizer, after 8000 hours of operation at TH15, revealed thin deposits of tungsten around the keeper, and within the upstream and downstream ends of the orifice. It is important to note that the amount of deposition in the EMT2 orifice was minimal as compared to what has been observed during the TH0 test segment of FT2.⁶

Thrust Magnitude and Direction

Shown in Fig. 23 is a comparison of the thrust calculated from electrical thruster parameters for FT2 and EMT2 and thrust measurements made during FT2 testing. The calculated thrust is based on the measured beam current and voltage, charge to mass ratio, and a constant accounting for beam divergence and multiply charged ion current of the beam. The proportionality constant is based on a curve fit to centerline double ion current measurements as a function of propellant utilization efficiency in a 30 cm, ring-cusp inert gas thruster.^{21, 22} The uncertainty in the calculated values is ± 2.3 percent. The thrust, a key performance parameter, has remained relatively constant at each test segment, over the past 21,000 hours of operation. The greatest discrepancy between calculated to measured thrust was seen during the second and current TH15 test segments. All thrust measurements for FT2 agree with the calculated thrust to within 9 percent for TH15, 2 percent for TH8, and 10 percent for TH0. Variations in measured thrust would indicate a higher doubly charged

ion content in the beam, operating whilst electron backstreaming, or higher beam divergence.

Shown in Fig. 24 is a comparison of the horizontal thrust vector angle, for FT2 and EMT2. Determination of the thrust vector is important for spacecraft trajectory analysis, as non-axial thrust must be accounted for, and corrected. For both thrusters, observed variations in the vertical and horizontal angle are about 0.2° and 0.4° , respectively. Small jumps of less than 0.2° occur when the power level is changed, with a trend to increasing the thrust vector angle as the thruster wears. Such shifts have been measured over the three test segments operated at the TH15 power point. A typical spacecraft gimbal system can easily compensate for the changes in thrust vector exhibited by FT2, over the past 23,000 hours. Overall, the average thrust vector has been relatively constant during operation over each test segment, with the exception of the first TH15 test segment. Variation of thrust vector as a function of power level, indicates a larger horizontal angle with an increase in power.¹⁸

Electrical Isolation Degradation

Loss of electrical isolation between critical components is another generic failure mode for ion thrusters. At the start of FT2 testing, all impedances were above 1 G Ω . However, degradation in the electrical isolation for neutralizer and discharge cathode components was first observed only 447 hours into FT2 testing.

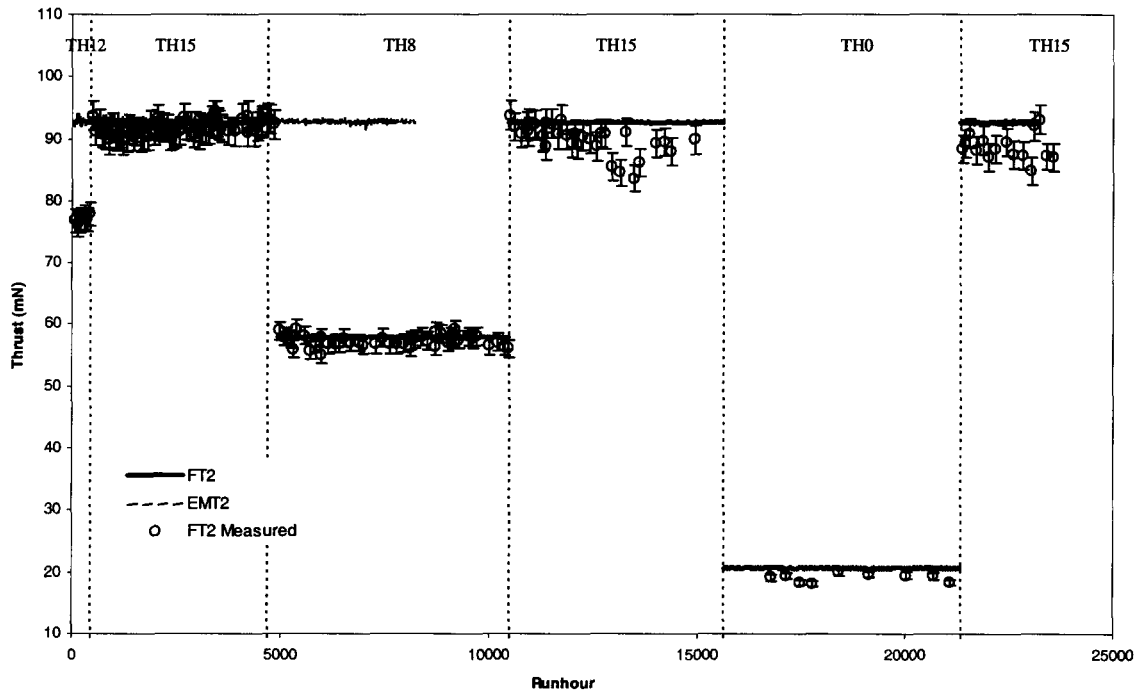


Fig. 23 Thrust Comparison for FT2 and EMT2

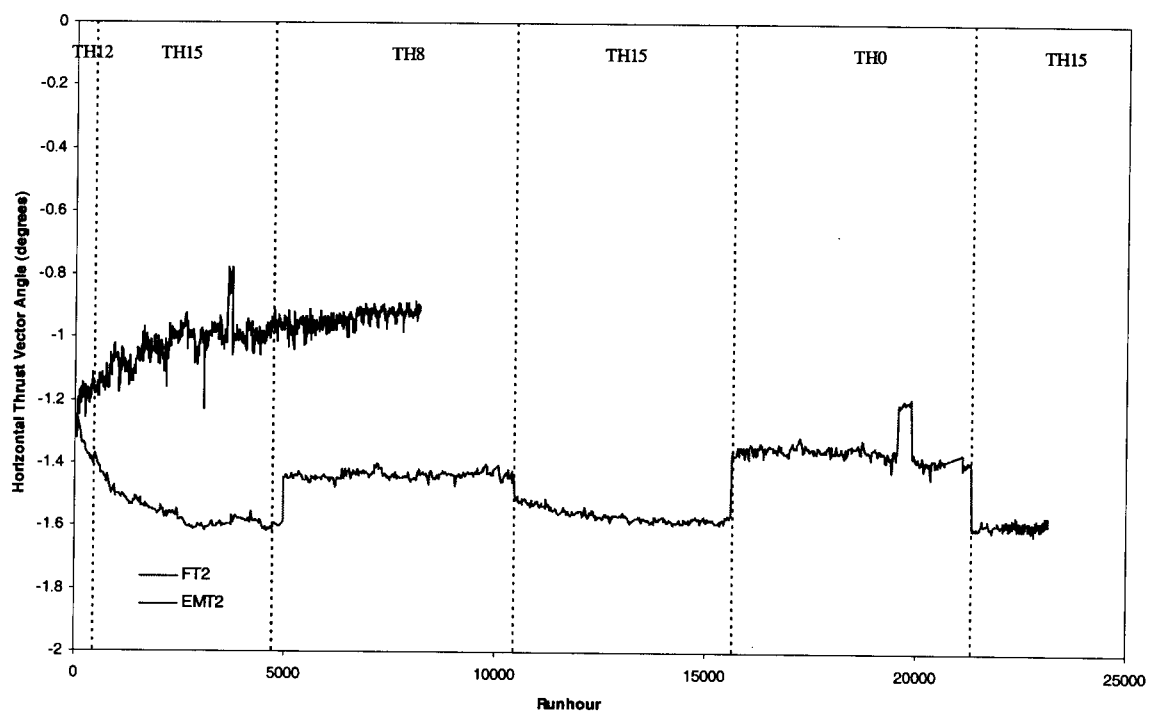


Fig. 24 Horizontal Thrust Vector Angle Comparison for FT2and EMT2

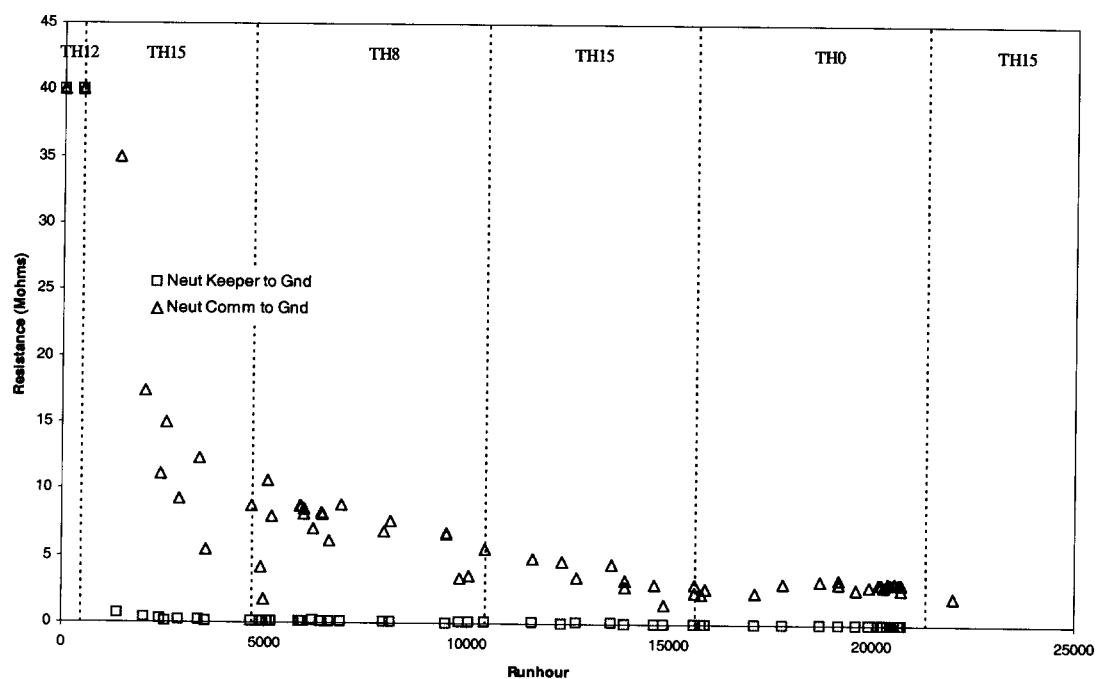


Fig. 25 FT2 Neutralizer Keeper and Neutralizer Common To Ground Resistance

Fig. 25 is a plot of neutralizer keeper and neutralizer common impedances to facility ground. The impedance of both components rapidly fell during the first 2000 hours of operation. The impedance for neutralizer keeper to ground dropped to from 10 GΩ to approximately 30-40 kW and has remained there to the present day. The cause of the degradation in the neutralizer keeper-facility ground impedance will not be determined until the neutralizer can be inspected after completion of the FT2 test. The impedance loss for neutralizer common to ground, however, decreased at a lower initial rate, but continued to decrease from 5000 to 15,000 hours, dropping from an initial value of 1 GW to 3 MW. During the TH0 test segment, from 15,617 to 21,306 hours, the neutralizer common to ground impedance remained constant. Possible causes for the reduction in neutralizer common and keeper to facility ground impedance include deterioration of wiring insulation and degradation of the neutralizer propellant flow isolator as well as carbon deposits back sputtered from the graphite panels, providing a conductive path to ground. It is possible to operate the thruster if either the neutralizer keeper or neutralizer common is shorted to facility ground however; the thruster would no longer be decoupled from ground.

Fig. 26 shows degradation of neutralizer keeper to neutralizer common impedance. The neutralizer keeper to common impedance fell most significantly during the first 2000 hours, and leveled off at approximately 3 MΩ by 15617 hours. Degradation of neutralizer keeper-

neutralizer common impedance, if severe enough, can cause thruster failure. If leakage current is sufficiently high, the neutralizer discharge cannot be maintained. At impedances above 100 Ω, neutralizer performance and margin from plume mode would be reduced, but the neutralizer would still provide sufficient electron current for beam neutralization. Possible causes for the reduction in neutralizer keeper-neutralizer common impedance include neutralizer heater radiation shielding contacting the neutralizer keeper and a conducting layer depositing on the ceramic used to isolate neutralizer keeper from neutralizer common.

Fig. 26 also shows degradation of discharge cathode common to anode impedance. At the start of testing the impedance was greater than 10 GW. From 2000 hours to 5000 hours, the resistance had decreased to approximately 4 MW. At approximately 5000 hours, the impedance began to increase, climbing up to 30 MW by 20,000 hours. Possible causes for the initial reduction in cathode common to anode impedance include a conducting layer depositing on the ceramic used to isolate cathode common from anode or a conductive path between pins in the thruster wiring cable connector. Degradation of cathode common-anode impedance can reduce discharge chamber performance, and if severe enough, can cause thruster failure.

As mentioned previously, an intermittent short developed between cathode keeper and cathode

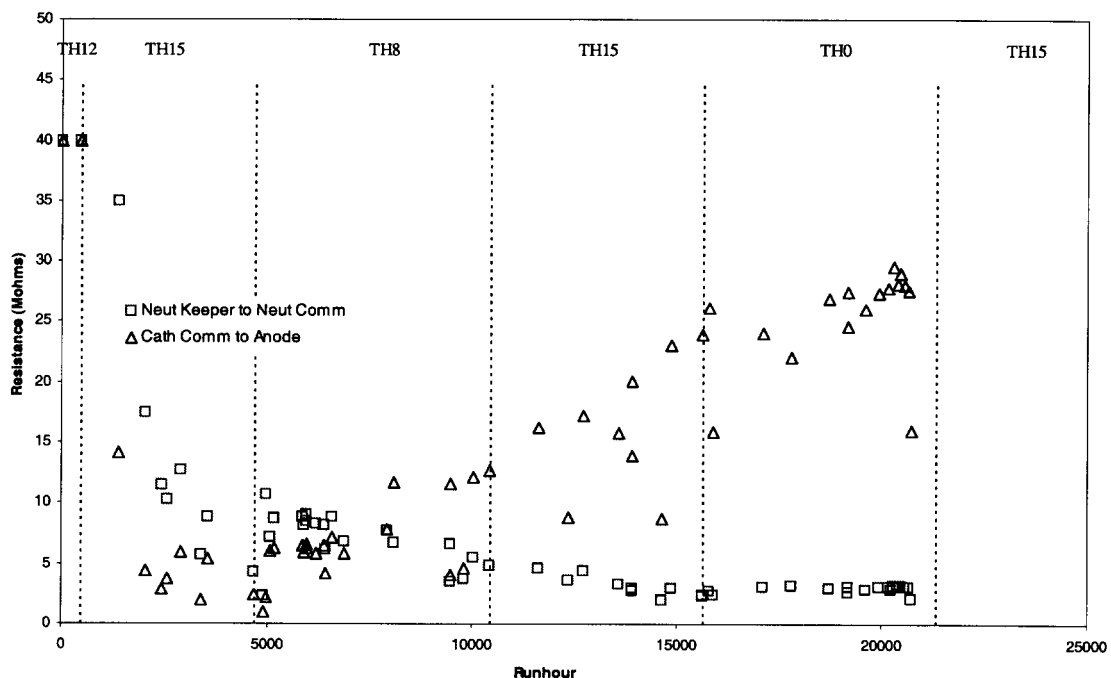


Fig. 26 FT2 Neutralizer Keeper to Neutralizer Common and Cathode Common to Anode Resistance

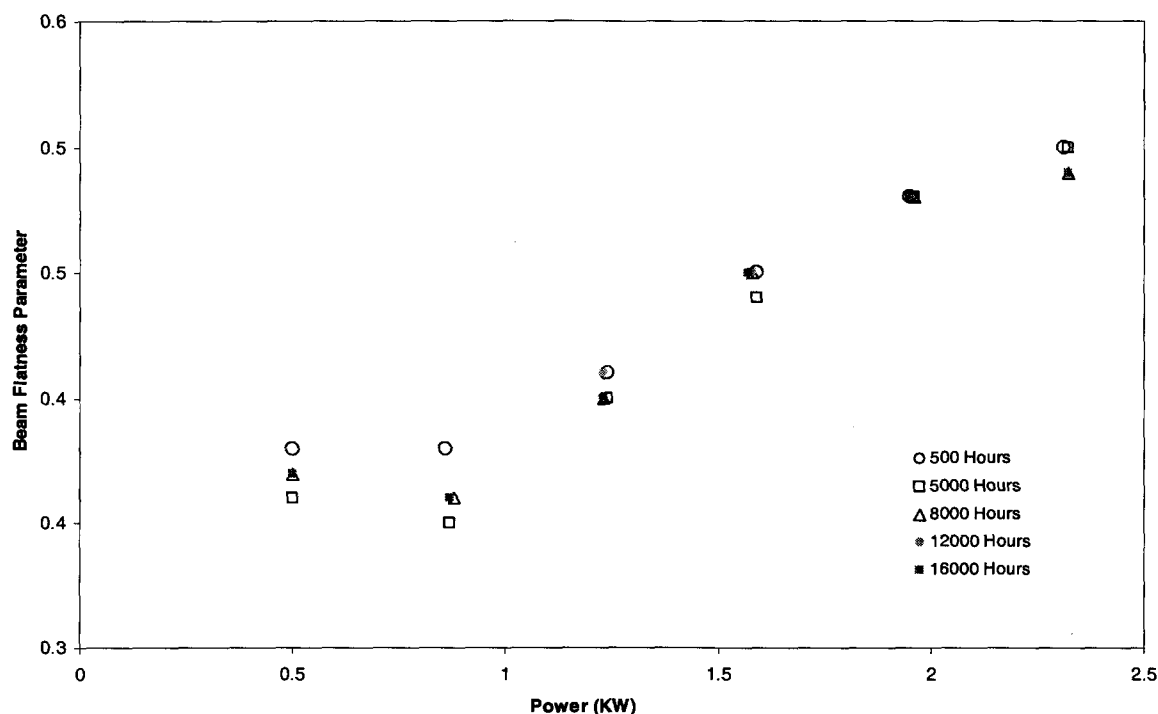


Fig. 27 FT2 Beam Flatness versus Power

common between 5,850 and 8,873 hours of the FT2 test; this caused the cathode keeper voltage to drop to ~0.4 V. At 8,873 hours the cathode keeper-cathode common short cleared when the cathode keeper orifice eroded. While the cathode keeper was shorted to cathode common, the discharge was more difficult to ignite on FT2. Prior to the short the discharge could be ignited with a 50 V open circuit laboratory power supply. While the short existed, the discharge could not be initiated with this supply and a 250 V start supply had to be used. Once the short cleared, the discharge could again be ignited using the 50 V power supply. It is important to note that all laboratory supplies used to ignite the FT2 discharge are at a lower voltage than that available on the DS1 flight PPU.

CONCLUSIONS

Over 23,500 hours of operation and 190 kg of Xenon have been accumulated with the DS1 flight spare thruster (FT2) during an on-going test. The thruster is performing well and no problems that would preclude the processing of 200 kg of xenon have been identified. Severe cathode keeper erosion was observed during and after FT2 operation at 1.5 kW; however, this erosion is not expected to cause thruster failure in the near term, as sensitive components such as the cathode heater wire do not appear to be eroding, and ignition characteristics have remained relatively unchanged. Concurrent to this,

cathode heater power and resistance have been decreasing at a steady rate, following an intermittent short that developed, and later cleared. During operation at the TH0 power level, an increasing keeper voltage, and loss of neutralizer flow rate margin, required to prevent plume mode was observed. Deposit formation within the orifice, during the TH0 test segment, resulted in a substantial decrease in the open area of the orifice, leading to possible concerns about the operation of cathodes at low flow conditions. It is believed that this deposit formation is responsible for the loss of neutralizer flow rate margin and the increasing keeper voltage. Degradation in the electrical isolation between neutralizer keeper to common and cathode common to anode has been observed during FT2 testing; however, the impedances remain sufficiently high, preventing any significant impact on thruster performance. Operation at the full power point is associated with the highest rate of accelerator grid erosion, resulting in an increase in the electron backstreaming limit, and pitting of the webbing of the upstream side. If operation of the thruster is continued at the full power point, reaching the upper limit of the accelerator power will be the first end of life criteria to be reached. This would not preclude the operation of the thruster at lower power levels, however.

ACKNOWLEDGMENTS

The authors would like to acknowledge the invaluable efforts of the many people who assisted in conducting this test and performing data analysis; they include Keith Goodfellow, Al Owens, Jay Polk, Bill Thogmartin, Bob Toomath, and Rob Kolasinski. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Christensen, J., et al., "Design and fabrication of a Flight Model 2.3 kW Ion Thruster for the Deep Space 1 Mission," AIAA-98-3327, July 1998.
2. Anderson, J. R., et al., "Results of an On-going Long Duration Ground Test of the DS1 Flight Spare Ion Engine," AIAA-99-2857, June 1999.
3. Polk, J. E., et al., "Demonstration of the NSTAR Ion Propulsion System on the Deep Space One Mission," 27th International Electric Propulsion Conference, October 2001.
4. Polk, J. E., et al., "Validation of NSTAR Propulsion system on the DS1 Mission," AIAA-99-2246, June 1999.
5. Polk, J. E., et al., "In-Flight Performance of the NSTAR Ion Propulsion System on the Deep Space One Mission," Z8_0304.PDF, IEEE Aerospace Conference Proceedings, March 2000.
6. Polk, J. E., et al., "An Overview of the Results from an 8200 Hour Wear Test of the NSTAR Ion Thruster," AIAA-99-2446, June 1999.
7. Anderson, J. R., et al., "Performance Characteristics of the NSTAR Ion Thruster During an On-Going Long Duration Ground Test," Z8_0303.PDF, IEEE Aerospace Conference Proceedings, March 2000.
8. Polk, J. E., et al., "A 1000-hour Wear Test of the NASA NSTAR Ion Thruster," AIAA-96-2717, July 1996.
9. Polk, J. E., et al., "The Effect of Engine Wear on Performance in the NSTAR 8000 Hour Ion Engine Endurance Test," AIAA-97-3387, July 1997.
10. Polk, J. E., et al., "In Situ, Time-Resolved Accelerator Grid Erosion Measurements in the NSTAR 8000 Hour Ion Engine Wear Test," IEPC-97-047, 1997.
11. Wang, J., et al., "Three-Dimensional Particle Simulations of NSTAR Ion Optics," 27th International Electric Propulsion Conference, October 2001.
12. Patterson, M. J., et al., "2.3 kW Ion Thruster Wear Test," AIAA-95-2516, July 1995.
13. Jahn, R. G., *The Physics of Electric Propulsion*, Mc-Graw Hill, New York, 1968.
14. Domonkos, M. T., "Thermographic Investigation of 3.2 mm Diameter Orificed Hollow Cathodes," AIAA 98-3793, July 1998.
15. Rawlin, V. K., et al., "NSTAR Flight Thruster Qualification Testing," AIAA-98-3936, July 1998.
16. Garner, C. E., et al., "Methods for Cryopumping Xenon," AIAA-96-3206, July 1996.
17. Goodfellow, K. D., et al., "An Experimental and Theoretical Analysis of Grid-short Clearing Capability of the NSTAR Ion Propulsion System," AIAA-99-2859, June 1999.
18. Polk, J. E., et al., "Behavior of the Thrust Vector in the NSTAR Ion Thruster," AIAA-98-3940, July 1998.
19. Engelbrecht, C. S., "NSTAR Xenon Feed System (XFS) Technical Requirements Document (TRD)," NSTAR Document ND-330, January 1997.
20. Ganapathi, G. B., et al., "Post-Launch Performance Characterization of the Xenon Feed System on Deep Space One," AIAA-99-2273, June 1999.
21. Patterson, M., et al., "NASA 30 cm Ion Thruster Development Status," AIAA-94-2849, June 1994.
22. Rawlin, V. K., "Operation of the J-Series Thruster Using Inert Gas," NASA TM-82977, November 1982.